

MODELING NATURAL REGENERATION OF
PONDEROSA PINE ON THE COCONINO
NATIONAL FOREST

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Final R

**FINAL REPORT ON RESEARCH JOINT VENTURE
AGREEMENT No. 28-JV**

98-156

**MODELING NATURAL REGENERATION
OF PONDEROSA PINE
ON THE
COCONINO NATIONAL FOREST**

January 31, 2003

**Submitted by Karen Goodwin
Principal Investigator, John Bailey**

SUMMARY OF STUDY RESULTS

Seedling Density: Number of seedlings per acre is more closely correlated to soil type than to stand structure or management history. The three study parameters that most accurately group the study stands by soil type in a discriminant analysis are (1) number of seedlings/acre/decade not under canopy, (2) elevation and (3) percent sand in soil.

Regeneration Response Models:

TES 546 & 650 Limestone (Adjusted Rsquare 0.827) – Predictor variables are (1) stand basal area (negative correlation), (2) percent dead & down wood <25cmd (positive correlation), (3) number of years since last cut (positive correlation) and (4) percent clay in soil (positive correlation).

TES 582 Productive Basalt (Adjusted Rsquare 0.583) – Predictor variables are (1) stand mean canopy (positive correlation), (2) percent dead & down wood <25cmd (negative correlation), (3) number of years since last cut (negative correlation) and (4) percent sand in soil (positive correlation).

Soil Compaction: Impaired soils were found on 65% of skid trails, 58% of openings, 37% of area under tree canopies, and 15% of area 1m from 9-12 year old seedling stems. Increasing soil bulk density negatively affected both seedling root and shoot length in a greenhouse study. The notable decrease in root length at bulk densities of 1.2-1.3gr/cc in the greenhouse study correlate with the low occurrence of bulk densities >1.2gr/cc found 1m from field seedlings.

Seedling Survival Following Prescribed Fire: Mortality of seedlings <1.3m tall was 100% in the path of fire. Mortality for seedlings 1.3-1.8m tall was 97% by the following spring. Average area burned was 78%. At current height growth rates, seedlings need at least 25-30 years to outgrow prescribed burns. Mean seedling survival rate from cohort competition for growing space is estimated to be 0.327.

Assuming two prescribed fires in 25 years, an estimated 100 seedlings/acre/decade are needed for 0.87 seedlings/acre/decade to survive to maturity, the approximate number needed to sustain 20-30 mature trees per acre. Seven of the 47 study stands (2 on basalt soils, 5 on limestone soils) have >100 seedlings/acre/decade.

Seedling Growth Rates and Effects of Browsing by Ungulates: Mean annual height growth for 3-12 year old seedlings is 3.50cm on limestone soils and 3.05cm on basalt soils. Browse damage by ungulates was on 52% of seedlings in 1999, with damage primarily on seedlings <0.5m high.

Around five exclosures fenced in May, 2001, seedlings browsed by elk only were 5% in 2001 and 9% in 2002, with most browse damage on seedlings >0.5m high. In May, 2002,

exclosures showed no increase in grass or forb basal stem, but had an estimated 50% increase in grass and forb basal stem by October, 2002. In October, 2002, newly germinated pipo seedlings were 2.95 times more numerous inside exclosures, and all germination was on light litter.

Seeds are Growing In...: Seedlings appear to be selecting for sheltered microsites; ie. by large dead & down logs, by rocks, and by scattered slash. Seedlings appear to be selecting against deep needle litter and bare soil and selecting for light to moderate grass cover and light needle litter.

Years Since Last Burned: Across all study shelterwood cut stands, a decent bivariate correlation seems to exist between the number of years since the stand was last control burned and seedling density.

Seedlings and Climate: Study data suggests a tendency for seedling density to be greater on stands that lie within the middle of the elevational range of ponderosa pine on the Coconino NF. Seedling density appears to be strongly correlated with precipitation of the year of seed pollination. Temperatures 0.5m above ground appear to be more extreme in stand openings and in open stands than in stands with high canopy. Seedling germination and early survival seem to be dependent on soils that arrive at field capacity quickly.

Relationship of Basal Area and Canopy: The ratio of basal area in square feet/acre to percent canopy cover on the study areas ranges from 2.12/1.00 to 4.57/1.00, with a mean ratio of 3.07/1.00. On average, if basal area is 100sq ft/acre, then canopy cover is approximately 33%. An attempt was made to use qmd and Ripley's $K(t)/\pi (d)^2$ to predict appropriate ba/canopy ratios for a variety of ponderosa pine stand structures. Regression hints at the relationships, but they are very weak.

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Academic Committee:

John Bailey, Committee Chair, School of Forestry, NAU (silviculture)
Steven Hart, School of Forestry, NAU (forest soils)
Joy Mast, Department of Geography, NAU (spatial analysis)
Tom Kolbe, School of Forestry, NAU (tree ecophysiology)

Principle of Determinism: Many antecedent events lead to increasing complexity of the determinism of a condition or event.

Study Objectives

- * Develop a regression model to predict natural regeneration of ponderosa pine (*Pinus ponderosa*, var. *scopulorum*) on the Coconino National Forest.
- * Report on any observed correlation between ponderosa pine seedling density or height growth and individual environmental factors affecting seedling germination and survival.
- * Explore the relationship between ponderosa pine stand basal area and canopy cover.

Study Design – Analytical Survey

Four Terrestrial Ecosystem Survey soil types were chosen for study:

- * **582** – Productive basalt clay loam, pipo/bunchgrass or pipo/quga, <10% slope
 - * **585** – Shallow rocky basalt clay loam, pipo/bunchgrass or pipo/quga, <10% slope
 - * **546** – Limestone fine sandy loam, pipo/bunchgrass or pipo/quga, <10% slope
 - * **650** – Limestone fine sandy loam, pipo/mixed conifer, <10% slope
- All stands were identified on the Coconino National Forest that contain at least 15 contiguous acres of one of the above soil types, and were either regen cut from 1985-95

(SH), commercially thinned prior to 1995 (CT), or were last cut prior to 1975 and had several seed trees per acre (DOG).

These stands were then grouped, sight unseen, by soil type, cut, years since cut, and elevation. One stand from each of the 45 groups was randomly drawn for survey and study. Some groups had one stand; other groups had many stands. Two additional stands were selected for study:

A stand on TES 585 soil in the Beaver Creek Watershed experiment that was seed cut in 1969 and has failed to regenerate.

Private property on the Blue Ridge Ranger District. It is the only area that could be found which meets all study criteria and in addition has been fenced from cattle grazing for several (14) years.

Through extensive pre-testing, the following survey design was found to be the most efficient for capturing within stand variability and for estimating parameter variances. Three 30m square (0.09ha or 0.22acre) plots were randomly placed in each study stand. Within each plot, all trees, seedlings, and stumps were mapped and measured. Measurements taken are:

All trees – species, mortality, dbh (or height if dbh < 1.0cm), damage or cause of death

Pipo seed trees – all of the above, plus height, age (on some), crown class, and relative amount of cones in crown and on ground

Pipo seedlings 3-12 years old -- height to nearest cm, age, type of microsite, basal area at seedling, degree of browse in current year, and whether or not under tree canopy

Within each plot, ground cover was identified at 1m intervals along each of 6 evenly spaced 30m transects for a total of 180 points. Canopy cover was read with a vertical projector at 30 evenly spaced grid points across each plot; basal area was also read with a 10x angle gauge at these points.

Soil samples at 0-15cm depth were collected at 10 random points across each study stand. These samples were combined by stand, sieved to 5mm, oven-dried, and classified by percent silt, clay, and sand, using the hydrometer method.

Additional surveys, sampling, and one greenhouse experiment were conducted to further explore the relationship between seedling response and selected environmental factors. These study methods are described where applicable in the following study results. Data is stored and was analyzed using SPSS Version 9.0. Plot maps are hand drawn, using within plot distance and direction coordinates of tree locations as well as additional individual tree data.

Study Results

Unless otherwise stated, seedling numbers in all study results are for ages 3-12 years, per acre, after the most recent cut, and adjusted to reflect the number present in one decade. Calculations and testing reported here are on untransformed data, unless otherwise stated. Means and distributions were calculated and tested both by individual plot and by stand, Means reported here are from stand averages. See the **attached table "Stand Averages"**.

1. Seedling Density and Soil Type:

One-way Analysis of Variance suggests that seedling density across the 47 study stands is more closely correlated with soil type (TES) than to stand structure and management history (Cut). See the **attached chart "Oneway Anova"**.

TES & Number of Seedlings	F=4.331	P =.009
TES & Number of Seedlings/seed tree	F=6.686	P= .001
Cut & Number of Seedlings	F=0.929	P= .403
Cut & Number of Seedlings/seed tree	F=0.439	P= .647

Discriminant Analysis supports the strong correlation between soil type and seedling density. TES soil type is used as the grouping factor, and 10 other non-colinear study parameters are used as canonical discriminant function coefficients. See the **attached chart "Discriminant"**. The three parameters that most accurately group the study stands by soil type are:

- * Number of seedlings/acre not under canopy
- * Elevation
- * Percent sand in soil

Stand Averages Includes Outliers

- | | |
|---|--|
| 1 = basal area (sq ft/acre, from trees) | 6 = # seed trees/acre |
| 2 = % canopy | 7 = # seedlings/seed tree |
| 3 = ba/canopy | 8 = # seedlings not under canopy |
| 4 = QMD (all trees, in inches) | 9 = % seedlings not under canopy |
| 5 = # seedlings post cut/acre/decade | 10 = # seedlings not under canopy/# seed trees |

<u>TES</u>	<u>Cut</u>	<u>(n)</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>	<u>9</u>	<u>10</u>
All DOG	(14)		131.55	43.57	3.02	11.06	78.07	23.23	3.36	30.89	39.56	1.33
All SH	(17)		62.23	20.59	3.02	15.89	35.59	13.32	2.67	34.02	95.59	2.55
All CT	(16)		115.38	36.63	3.15	10.46	77.75	40.28	1.93	40.72	52.37	1.01
650 DOG	(2)		132.74	46.00	2.89	13.29	309.50	15.20	20.36	132.62	42.85	8.73
650 SH	(2)		38.55	11.50	3.35	14.72	116.00	8.36	13.88	99.76	86.00	11.93
650 CT	(3)		138.56	40.67	3.41	9.53	117.00	31.92	3.63	65.27	55.79	2.04
546 DOG	(4)		119.44	49.00	2.44	10.35	46.75	20.14	2.30	21.82	46.67	1.08
546 SH	(5)		80.14	28.20	2.84	9.85	46.22	10.03	4.61	36.46	78.88	3.64
546 CT	(3)		125.71	43.33	2.90	11.43	129.33	32.43	3.99	64.86	50.15	2.00
582 DOG	(6)		136.91	39.17	3.49	12.30	31.00	30.40	1.10	8.31	26.81	0.27
582 SH	(6)		55.56	19.83	2.80	13.44	19.74	16.47	1.20	13.97	70.77	0.85
582 CT	(6)		95.26	33.50	2.84	10.31	75.50	46.12	1.64	38.51	51.01	0.83
585 DOG	(2)		138.48	43.50	3.18	9.70	50.50	15.96	3.16	15.10	29.90	0.95
585 SH	(4)		61.67	16.75	3.68	16.10	5.88	15.20	0.39	3.58	60.88	0.24
585 CT	(4)		120.43	33.25	3.62	10.66	13.75	43.71	0.31	7.55	54.91	0.17

Oneway Anova - TES (650, 546, 582,585)

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
#seedlings/acre age 3-12, post cut, adjusted for decade	Between Groups	110207.03	3	36735.677	4.331	.009
	Within Groups	364716.01	43	8481.768		
	Total	474923.04	46			
ratio of seedlings/seed trees, numsepos/numsdtr	Between Groups	1238.327	3	412.776	6.686	.001
	Within Groups	2654.884	43	61.741		
	Total	3893.210	46			
# seedlings per acre age 3-12, post cut, adjusted for decade, no canopy	Between Groups	49390.074	3	16463.358	7.955	.000
	Within Groups	88989.506	43	2069.523		
	Total	138379.58	46			
ratio of seedlings/acre/decade, post cut, not under canopy to seed trees	Between Groups	852.967	3	284.322	5.222	.004
	Within Groups	2341.192	43	54.446		
	Total	3194.159	46			

canopy to # seed trees

Oneway Anova - Cut (DOG, SH, CT)

ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
#seedlings/acre age 3-12, post cut, adjusted for decade	Between Groups	19241.993	2	9620.997	.929	.403
	Within Groups	455681.04	44	10356.387		
	Total	474923.04	46			
ratio of seedlings/seed trees, numsepos/numsdtr	Between Groups	76.206	2	38.103	.439	.647
	Within Groups	3817.004	44	86.750		
	Total	3893.210	46			
# seedlings per acre age 3-12, post cut, adjusted for decade, no canopy	Between Groups	769.495	2	384.748	.123	.885
	Within Groups	137610.08	44	3127.502		
	Total	138379.58	46			
ratio of seedlings/acre/decade, post cut, not under canopy to # seed trees	Between Groups	147.288	2	73.644	1.063	.354
	Within Groups	3046.871	44	69.247		
	Total	3194.159	46			

canopy to # seed trees

Discriminant

Analysis Case Processing Summary

Unweighted Cases		N	Percent
Valid		44	93.6
Excluded	Missing or out-of-range group codes	0	.0
	At least one missing discriminating variable	3	6.4
	Both missing or out-of-range group codes and at least one missing discriminating variable	0	.0
	Total	3	6.4
Total		47	100.0

Group Statistics

tes code 585=1 582=2 546=3 650=4		Mean	Std. Deviation	Valid N (listwise)	
				Unweighted	Weighted
1	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	7.4700	7.8664	10	10.000
	# of years since last cut	15.7000	14.7351	10	10.000
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	90.0560	50.0055	10	10.000
	ELEVATION IN FEET	7270.0000	241.7529	10	10.000
	% total sand in soil	49.3000	6.2370	10	10.000
	% of clay in soil	20.5000	2.7588	10	10.000
	% GROUND COVERED IN LITTER <2CM DEEP	52.7200	14.5761	10	10.000
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	6.7300	2.4855	10	10.000
	% GROUND COVERED BY GRASSES BASAL	7.3100	5.5691	10	10.000
	bd opening, adjusted to 1.00 undisturbed	1.2070	.1849	10	10.000

Group Statistics

tes code 585=1 582=2 546=3 650=4		Mean	Std. Deviation	Valid N (listwise)	
				Unweighte d	Weighted
2	# seedlings/acre. post cut, per decade, age 3-12, not under canopy	11.8867	9.7976	15	15.000
	# of years since last cut	23.0000	18.1816	15	15.000
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	90.9233	41.3714	15	15.000
	ELEVATION IN FEET	7336.6667	252.4640	15	15.000
	% total sand in soil	45.9333	5.7005	15	15.000
	% of clay in soil	20.2667	2.4919	15	15.000
	% GROUND COVERED IN LITTER <2CM DEEP	46.6533	12.7022	15	15.000
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	5.8133	2.5698	15	15.000
	% GROUND COVERED BY GRASSES BASAL	8.1333	3.9435	15	15.000
	bd opening, adjusted to 1.00 undisturbed	1.3653	.2130	15	15.000
3	# seedlings/acre. post cut, per decade, age 3-12, not under canopy	38.6792	54.6951	12	12.000
	# of years since last cut	14.1667	7.8258	12	12.000
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	100.0342	33.6048	12	12.000
	ELEVATION IN FEET	7100.0000	155.2125	12	12.000
	% total sand in soil	56.5000	5.9467	12	12.000
	% of clay in soil	19.5000	2.1532	12	12.000
	% GROUND COVERED IN LITTER <2CM DEEP	49.5583	13.7670	12	12.000
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	5.6417	2.1690	12	12.000
	% GROUND COVERED BY GRASSES BASAL	6.6500	2.7141	12	12.000
	bd opening, adjusted to 1.00 undisturbed	1.2750	.2728	12	12.000

Group Statistics

tes code 585=1 582=2 546=3 650=4		Mean	Std. Deviation	Valid N (listwise)	
				Unweighte d	Weighted
4	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	108.4300	83.9005	7	7.000
	# of years since last cut	12.8571	8.3152	7	7.000
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	93.8586	41.3197	7	7.000
	ELEVATION IN FEET	7357.1429	105.7850	7	7.000
	% total sand in soil	45.7143	4.9570	7	7.000
	% of clay in soil	19.8571	2.4103	7	7.000
	% GROUND COVERED IN LITTER <2CM DEEP	59.9143	12.5533	7	7.000
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	7.8286	1.5217	7	7.000
	% GROUND COVERED BY GRASSES BASAL	5.2429	5.8824	7	7.000
	bd opening, adjusted to 1.00 undisturbed	1.2029	.2788	7	7.000
Total	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	33.5491	55.0792	44	44.000
	# of years since last cut	17.3182	14.0096	44	44.000
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	93.6780	40.3079	44	44.000
	ELEVATION IN FEET	7260.2273	226.8540	44	44.000
	% total sand in soil	49.5455	7.1867	44	44.000
	% of clay in soil	20.0455	2.4011	44	44.000
	% GROUND COVERED IN LITTER <2CM DEEP	50.9341	13.7209	44	44.000
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	6.2955	2.3657	44	44.000
	% GROUND COVERED BY GRASSES BASAL	7.0818	4.3895	44	44.000
	bd opening, adjusted to 1.00 undisturbed	1.2789	.2379	44	44.000

Analysis 1

Stepwise Statistics

Pairwise Group Comparisons^{a,b,c}

Step	tes code 585=1		1	2	3	4
1	1	F		.061	2.758	21.791
		Sig.		.807	.105	.000
	2	F	.061		2.485	23.096
		Sig.	.807		.123	.000
	3	F	2.758	2.485		11.167
		Sig.	.105	.123		.002
	4	F	21.791	23.096	11.167	
		Sig.	.000	.000	.002	
2	1	F		.989	6.662	10.676
		Sig.		.381	.003	.000
	2	F	.989		14.042	11.651
		Sig.	.381		.000	.000
	3	F	6.662	14.042		10.800
		Sig.	.003	.000		.000
	4	F	10.676	11.651	10.800	
		Sig.	.000	.000	.000	
3	1	F		1.146	6.609	7.854
		Sig.		.343	.001	.000
	2	F	1.146		14.965	7.728
		Sig.	.343		.000	.000
	3	F	6.609	14.965		12.553
		Sig.	.001	.000		.000
	4	F	7.854	7.728	12.553	
		Sig.	.000	.000	.000	

a. 1, 40 degrees of freedom for step 1.

b. 2, 39 degrees of freedom for step 2.

c. 3, 38 degrees of freedom for step 3.

Summary of Canonical Discriminant Functions

Eigenvalues

Function	Eigenvalue	% of Variance	Cumulative %	Canonical Correlation
1	1.281 ^a	63.7	63.7	.749
2	.729 ^a	36.3	100.0	.649
3	.000 ^a	.0	100.0	.016

a. First 3 canonical discriminant functions were used in the analysis.

Wilks' Lambda

Test of Function(s)	Wilks' Lambda	Chi-square	df	Sig.
1 through 3	.254	54.202	9	.000
2 through 3	.578	21.635	4	.000
3	1.000	.009	1	.922

Standardized Canonical Discriminant Function Coefficients

	Function		
	1	2	3
# seedlings/acre, post cut, per decade, age 3-12, not under canopy	.082	1.022	-.017
ELEVATION IN FEET	-.720	.169	.748
% total sand in soil	.944	.109	.473

Structure Matrix

	Function		
	1	2	3
% total sand in soil	.715*	-.046	.698
% GROUND COVERED BY DEAD & DOWN ^a <25CM DIAMETER	-.354*	.097	.146
# of years since last cut ^a	.068*	-.024	-.057
# seedlings/acre, post cut, per decade, age 3-12, not under canopy	-.001	.975*	-.221
ba (SQ FT/ACRE) computed from 10-factor angle gauge ^a	-.070	-.261*	.138
% GROUND COVERED BY GRASSES BASAL ^a	.060	.209*	.169
% GROUND COVERED IN LITTER <2CM DEEP ^a	.114	.119*	.078
ELEVATION IN FEET	-.452	.051	.890*
bd opening, adjusted to 1.00 undisturbed ^a	-.003	.082	-.330*
% of clay in soil ^a	-.086	.121	.133*

Pooled within-groups correlations between discriminating variables and standardized canonical discriminant functions

Variables ordered by absolute size of correlation within function.

*. Largest absolute correlation between each variable and any discriminant function

a. This variable not used in the analysis.

Functions at Group Centroids

tes code 585=1 582=2 546=3 650=4	Function		
	1	2	3
1	-.122	-.604	2.490E-02
2	-.892	-.510	-1.368E-02
3	1.694	.120	-6.251E-03
4	-.818	1.750	4.463E-03

Unstandardized canonical discriminant functions evaluated at group means

Classification Statistics

Prior Probabilities for Groups

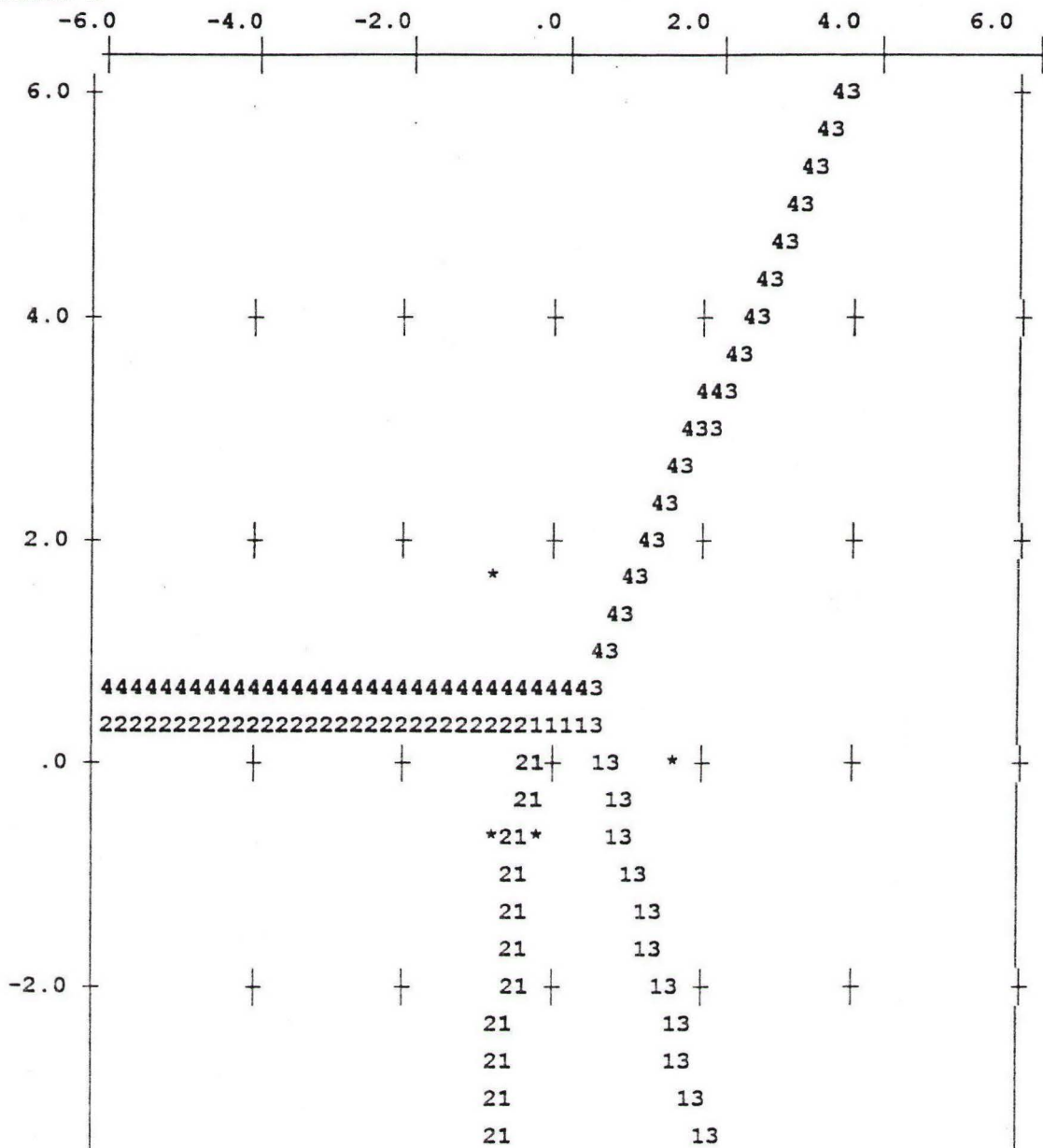
tes code 585=1 582=2 546=3 650=4	Prior	Cases Used in Analysis	
		Unweighte d	Weighted
1	.250	10	10.000
2	.250	15	15.000
3	.250	12	12.000
4	.250	7	7.000
Total	1.000	44	44.000

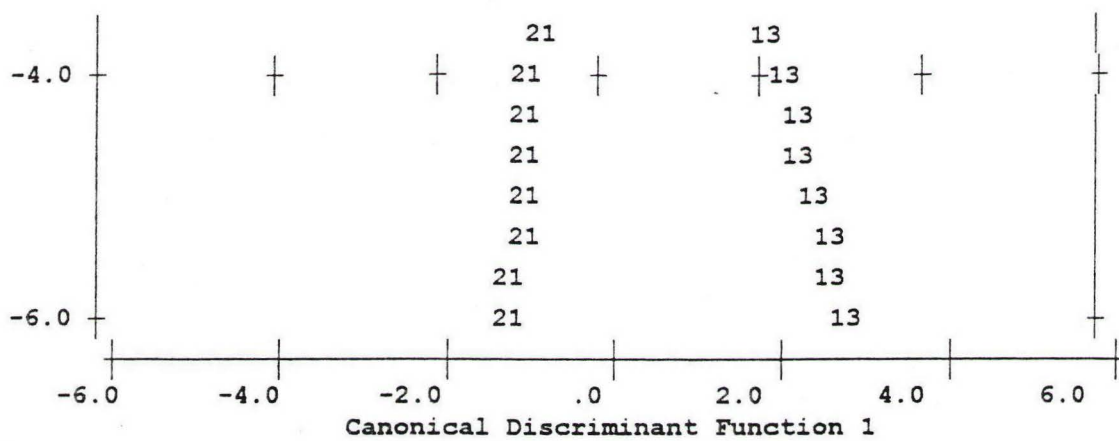
Territorial Map

(Assuming all functions but the first two are zero)

Canonical Discriminant

Function 2



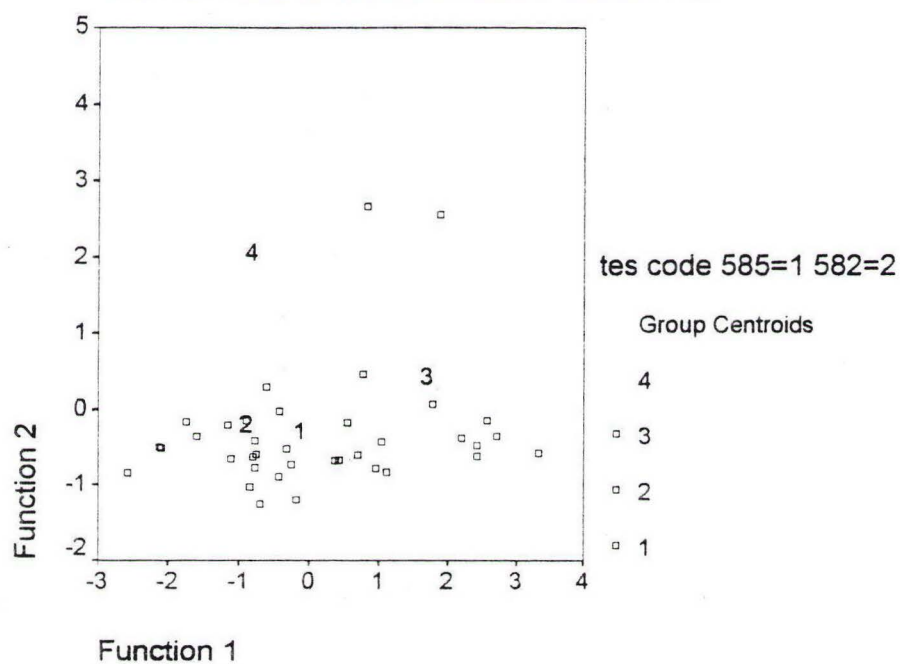


Symbols used in territorial map

Symbol	Group	Label
1	1	
2	2	
3	3	
4	4	
*		Indicates a group centroid

1 1
2 2
3 3
4 4
* Indicates a group centroid

Canonical Discriminant Functions



Classification Results^{b,c}

		tes code 585=1 582=2 546=3 650=4	Predicted Group Membership				Total
			1	2	3	4	
Original	Count	1	5	3	2	0	10
		2	3	12	0	0	15
		3	2	0	9	1	12
		4	1	2	0	4	7
	%	1	50.0	30.0	20.0	.0	100.0
		2	20.0	80.0	.0	.0	100.0
		3	16.7	.0	75.0	8.3	100.0
		4	14.3	28.6	.0	57.1	100.0
Cross-validated ^a	Count	1	4	4	2	0	10
		2	5	9	1	0	15
		3	3	0	7	2	12
		4	1	2	0	4	7
	%	1	40.0	40.0	20.0	.0	100.0
		2	33.3	60.0	6.7	.0	100.0
		3	25.0	.0	58.3	16.7	100.0
		4	14.3	28.6	.0	57.1	100.0

a. Cross validation is done only for those cases in the analysis. In cross validation, each case is classified by the functions derived from all cases other than that case.

b. 68.2% of original grouped cases correctly classified.

c. 54.5% of cross-validated grouped cases correctly classified.

2. Regeneration Response Models:

Regeneration response appears to be so closely correlated to the soil types in this study, that one regression model cannot estimate seedling response, even when soil type is one of the predictors. The four environmental factors that best predict seedling response are similar on both limestone and basalt soils, but soil type reverses the correlation of each predictor variable to seedling density.

- * Greater seedling density is correlated with low basal area on limestone soils, but high canopy cover on basalt soils.

- * The percent of ground covered by small (<25cm) dead and down woody material is positively associated with seedling density on limestone soils and negatively associated with seedling density on basalt soils, even though the range, mean, and median of percent woody material is similar on both soil types. The negative correlation on basalt soils is puzzling. Welch and Klemmedson (1975) found the weight of N by soil volume on the Coconino NF was greater on limestone soils than on basalts. Dead and down woody material can immobilize soil nitrogen under some conditions, which might reduce already low available soil nitrogen on basalt soils. However, Kolb et al (1999) found basalt soils on the Coconino NF had significantly greater concentrations of N than limestone soils; but they also found that potted Douglas-fir seedlings grown in the limestone soil had significantly greater concentrations of foliar N than those grown in the basalt soil.

- * On limestone soils, seedling response increases with the number of years since the stand was last cut, yet this relationship is reversed on basalt soils. Data from this study also indicates that seedling response on both limestone and basalt soils is stimulated for the first few years after prescribed fire, then tapers off. Sackett (1984) observed a similar response after fire. If soil nitrogen is relatively lower on basalt soils, the release of nitrogen by ground fire or disturbance may stimulate regeneration for a few years.

- * Seedling density is positively correlated with a relatively higher percentage of clay in the limestone soils but with a higher percentage of sand in the basalt soils. The mean and range in percent of clay is not significantly different among the four study soil types, but the range and mean in percent of sand is significantly higher on TES 546 (limestone pipo/bunchgrass) soils. See the **attached chart "Oneway – Soil Texture."**

The percent of soil moisture at saturation, field capacity, and wilting point differ for limestone and basalt soils on the Coconino NF (Heidmann and King 1992). Greater amounts of clay in a sandy limestone soil would increase its field capacity and thus the amount of moisture retained after drainage. Greater amounts of sand in a basalt soil would reduce its wilting point and thus make water still available to plants at lower levels of soil moisture. Both effects would likely enhance the length of time that soil water is available to seedlings.

Percent Soil Moisture:	<u>Sandy Limestone</u>	<u>Clay Loam Basalt</u>
------------------------	------------------------	-------------------------

Saturated	25%	47%
Field Capacity	10%	35%
Wilting Point	2%	10%

Soil compaction appears to be greatly affecting seedling density, but soil bulk density was not a good predictor for the models. Soil compaction varies within each stand, so a stand average for soil bulk density is not an accurate predictor for the model.

The models were developed by hand fitting predictor variables to achieve the best balance of high Durbin-Watson and t values, good standard error to standard deviation ratios, low colinearity, and good post hoc tests. Three of the 47 stands were removed from analysis; values for their response variable were outliers and were functioning as leverage points. See the **attached charts "Regression – Seedling Response..."**

For each model, the number of seedlings per acre per decade includes only those seedlings not under canopy; thus the equations predict the response of seedlings that are located where they may attain maturity. The six TES 585 (shallow rocky basalt) stands were omitted from the model for basalt soils. Seedling response differed so greatly between TES 585 and TES 582 (productive basalt) stands that one equation could not predict seedling density on both soils – another example of the extent to which soil type is affecting ponderosa pine regeneration.

Regeneration Model - TES 546 & 650: Adjusted R Square = 0.827

Number of seedlings/acre/decade not under canopy =

$$-374.304 + [-2.289 \text{ stand basal area (ft /acre)}] + [388.580 \text{ log percent dead \& down <25cmd}] + [5.612 \text{ \# years since last cut}] + [14.097 \text{ percent clay in soil}]$$

Regeneration Model - TES 582: Adjusted R Square = 0.583

Number of seedlings/acre/decade not under canopy =

$$-1.550 + [37.518 \% \text{ stand mean canopy}] + [-2.766 \text{ percent dead \& down <25cmd}] + [-18.133 \text{ log \# years since last cut}] + [0.880 \text{ percent sand in soil}]$$

To test the models, linear regressions were used to correlate, for each study stand, the seedling density predicted by the appropriate model with the observed seedling density. Despite the large constant in the limestone soil model, predicted seedling densities are all positive values. See the **attached charts "Regression – Predicted vs. Observed..."** Model predictions were moderately well correlated with observations.

- * TES 546 & 650: Adjusted R Square = 0.860
- * TES 582: Adjusted R Square = 0.695

Oneway - Soil Texture - TES 1 = 585, TES 2 = 582
TES 3 = 546, TES 4 = 650

Descriptives

		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean	
						Lower Bound	Upper Bound
% total sand	1	10	49.3000	6.2370	1.9723	44.8383	53.7617
	2	17	44.6471	6.5378	1.5856	41.2856	48.0085
	3	12	56.5000	5.9467	1.7167	52.7216	60.2784
	4	7	45.7143	4.9570	1.8736	41.1299	50.2987
	Total	46	48.9130	7.6647	1.1301	46.6369	51.1892
% silt	1	10	30.2000	5.9404	1.8785	25.9505	34.4495
	2	17	35.2941	7.6138	1.8466	31.3794	39.2088
	3	12	24.0000	7.2488	2.0926	19.3943	28.6057
	4	7	34.4286	4.7208	1.7843	30.0626	38.7946
	Total	46	31.1087	8.0918	1.1931	28.7057	33.5117
% clay	1	10	20.5000	2.7588	.8724	18.5265	22.4735
	2	17	20.0588	2.5610	.6211	18.7421	21.3756
	3	12	19.5000	2.1532	.6216	18.1319	20.8681
	4	7	19.8571	2.4103	.9110	17.6280	22.0863
	Total	46	19.9783	2.4266	.3578	19.2576	20.6989

Descriptives

		Minimum	Maximum
% total sand	1	39.00	58.00
	2	32.00	56.00
	3	49.00	67.00
	4	39.00	55.00
	Total	32.00	67.00
% silt	1	24.00	44.00
	2	24.00	52.00
	3	10.00	34.00
	4	28.00	43.00
	Total	10.00	52.00
% clay	1	17.00	24.00
	2	16.00	24.00
	3	17.00	23.00
	4	17.00	23.00
	Total	16.00	24.00

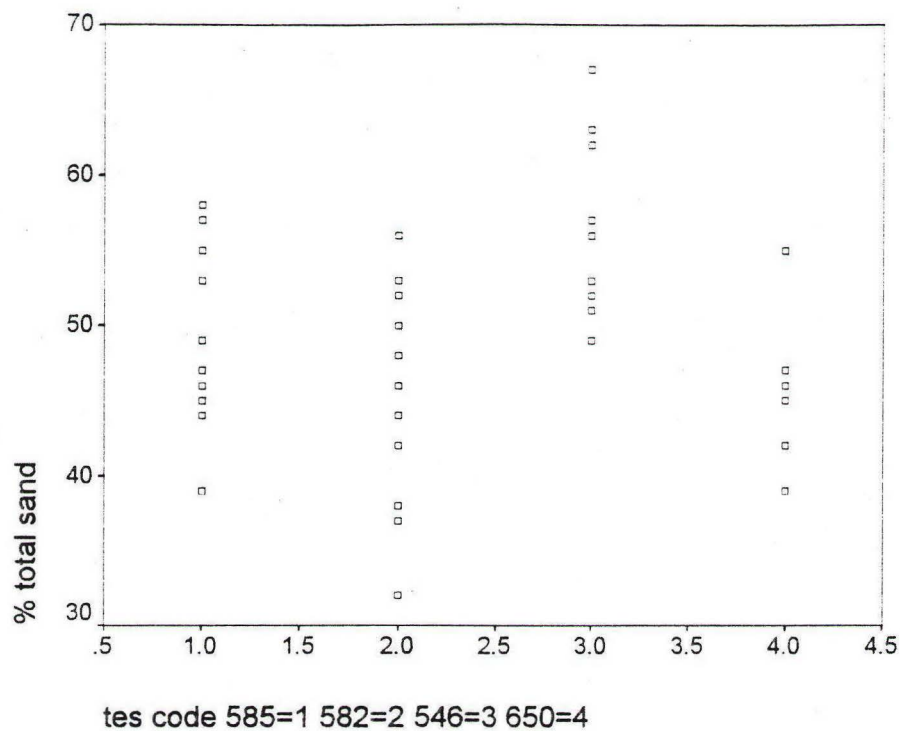
Test of Homogeneity of Variances

	Levene Statistic	df1	df2	Sig.
% total sand	.658	3	42	.582
% silt	1.018	3	42	.394
% clay	.433	3	42	.730

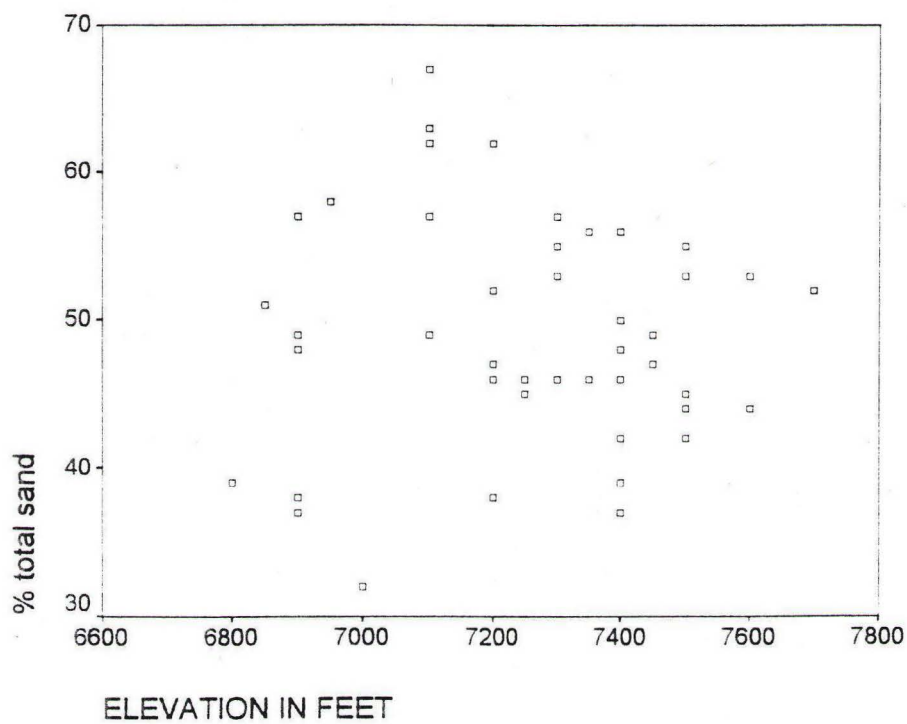
ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
% total sand	Between Groups	1073.241	3	357.747	9.568	.000
	Within Groups	1570.411	42	37.391		
	Total	2643.652	45			
% silt	Between Groups	989.613	3	329.871	7.080	.001
	Within Groups	1956.844	42	46.592		
	Total	2946.457	45			
% clay	Between Groups	5.680	3	1.893	.307	.820
	Within Groups	259.298	42	6.174		
	Total	264.978	45			

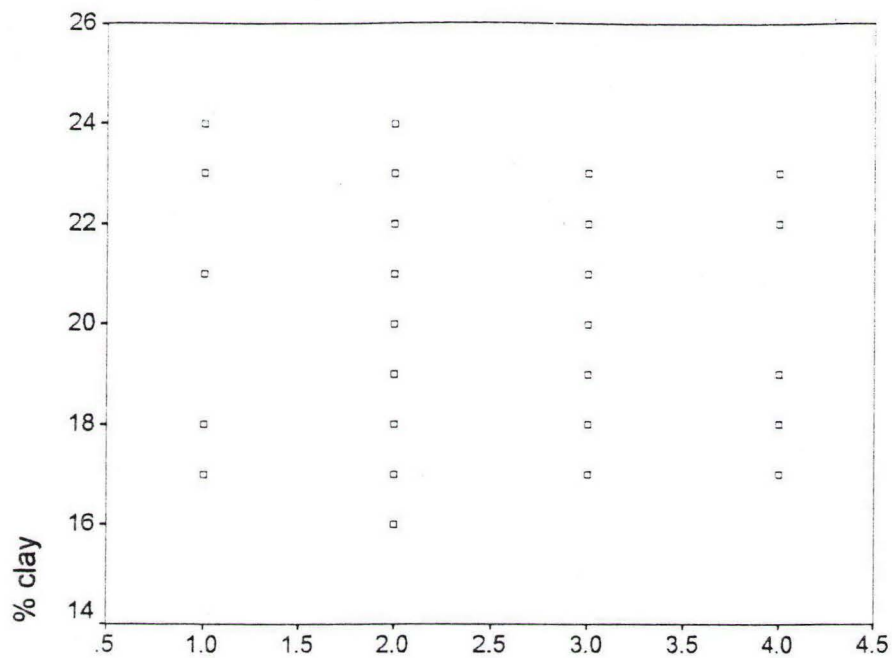
Graph



Graph

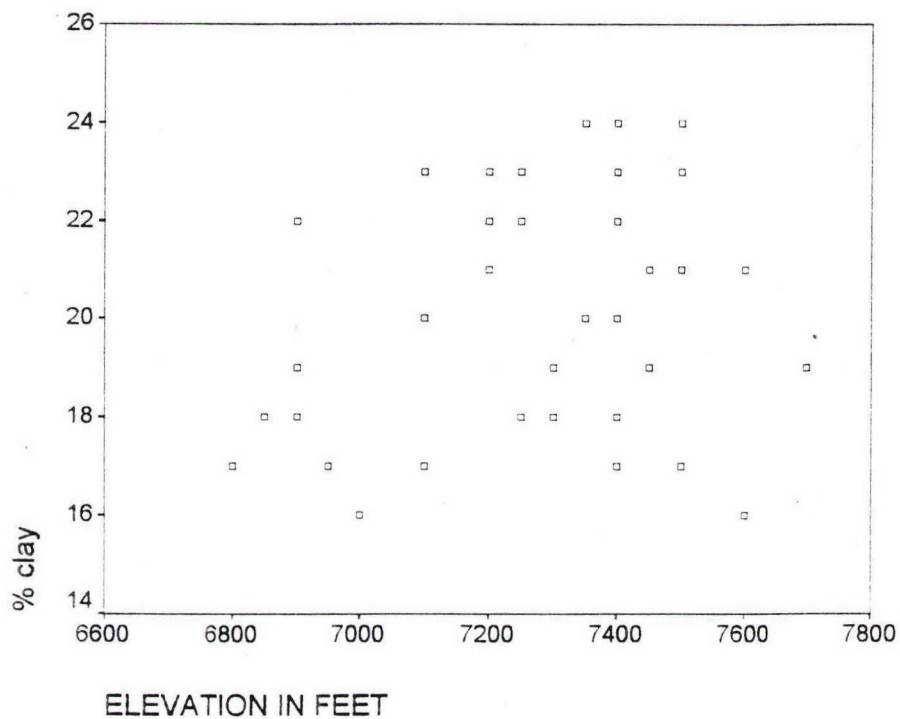


Graph



tes code 585=1 582=2 546=3 650=4

Graph



Graph

Regression - Seedling Response on Limestone Soils TES 546 & 650

Descriptive Statistics

	Mean	Std. Deviation	N
# seedlings/acre, post cut, per decade, age 3-12, not under canopy	66.9467	74.5155	18
ba (SQ FT/ACRE) computed from 10-factor angle gauge	96.5850	36.2696	18
log, % ground covered with dead & down wood <25cmd	.7847	.1601	18
# of years since last cut	14.00	7.90	18
% of clay in soil	19.7778	2.1572	18

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.932 ^a	.868	.827	30.9488	1.729

a. Predictors: (Constant), % of clay in soil, # of years since last cut, log, % ground covered with dead & down wood <25cmd, ba (SQ FT/ACRE) computed from 10-factor angle gauge

b. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	81941.744	4	20485.436	21.387	.000 ^a
	Residual	12451.790	13	957.830		
	Total	94393.535	17			

a. Predictors: (Constant), % of clay in soil, # of years since last cut, log, % ground covered with dead & down wood <25cmd, ba (SQ FT/ACRE) computed from 10-factor angle gauge

b. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-374.304	86.482		-4.328	.001
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	-2.289	.282	-1.114	-8.126	.000
	log, % ground covered with dead & down wood <25cmd	388.580	52.813	.835	7.358	.000
	# of years since last cut	5.612	1.203	.595	4.663	.000
	% of clay in soil	14.097	3.638	.408	3.875	.002

Coefficients^a

Model		95% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	-561.138	-187.471		
	ba (SQ FT/ACRE) computed from 10-factor angle gauge	-2.897	-1.680	.540	1.852
	log, % ground covered with dead & down wood <25cmd	274.484	502.677	.788	1.269
	# of years since last cut	3.012	8.212	.623	1.606
	% of clay in soil	6.238	21.956	.915	1.093

a. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

Residuals Statistics^a

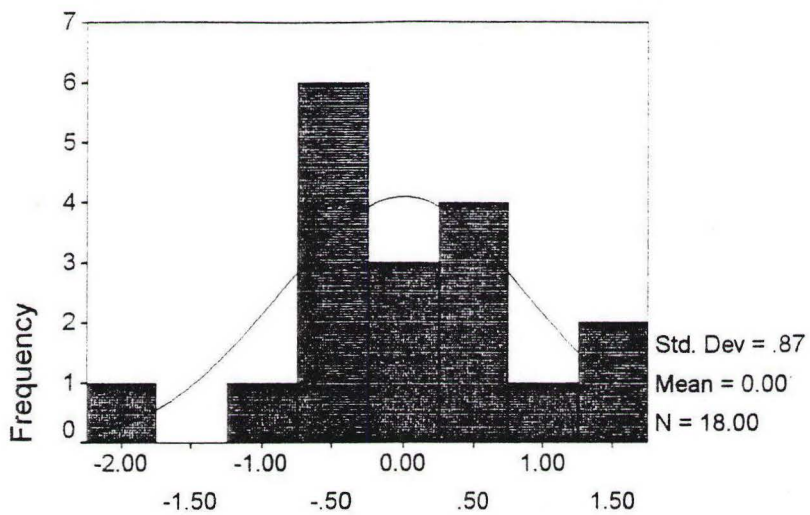
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	1.3706	209.5340	66.9467	69.4270	18
Residual	-60.5068	48.7539	1.311E-13	27.0640	18
Std. Predicted Value	-.945	2.054	.000	1.000	18
Std. Residual	-1.955	1.575	.000	.874	18

a. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

Charts

Histogram

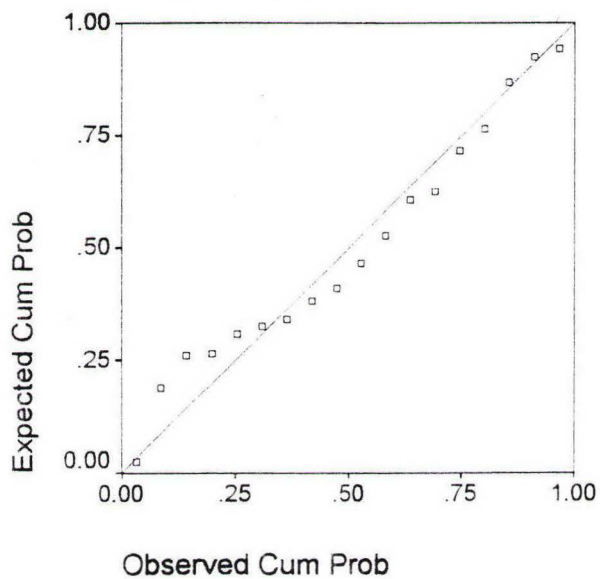
Dependent Variable: # seedlings/acre, post c



Regression Standardized Residual

Normal P-P Plot of Regression Sta

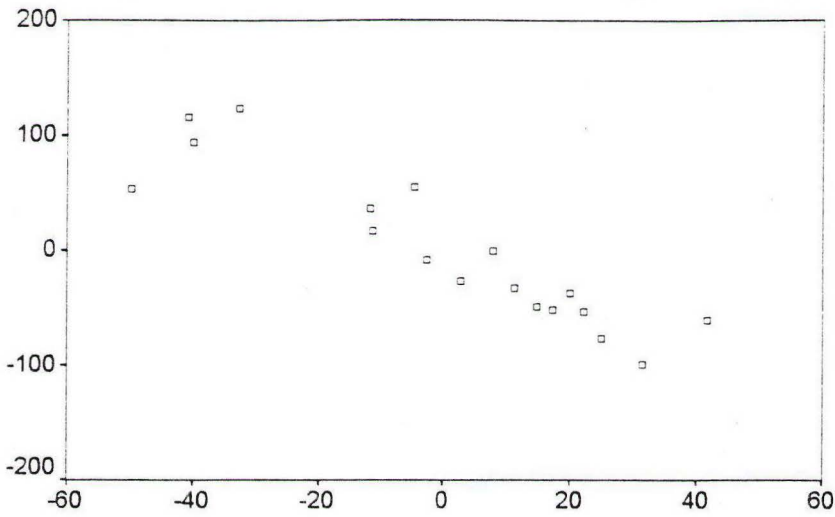
Dependent Variable: # seedlings/a



seedlings/acre, post cut, per decade, age 3-12

Partial Regression Plot

Dependent Variable: # seedlings/acre, pos

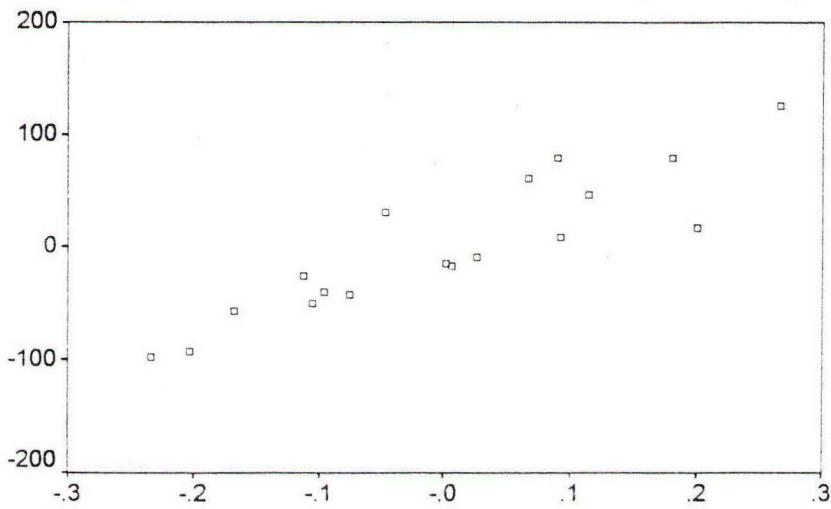


ba (SQ FT/ACRE) computed from 10-factor angle gauge

seedlings/acre, post cut, per decade, age 3-12

Partial Regression Plot

Dependent Variable: # seedlings/acre, pos

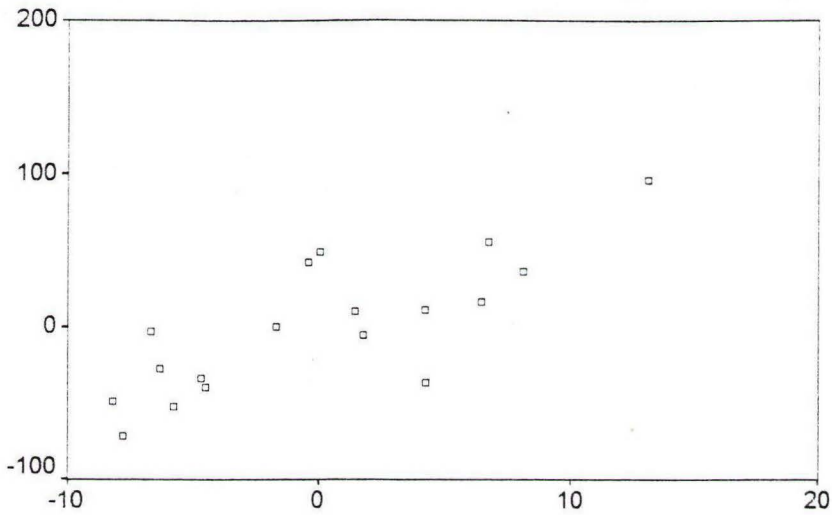


log, % ground covered with dead & down wood <25cmd

seedlings/acre, post cut, per decade, age 3-12

Partial Regression Plot

Dependent Variable: # seedlings/acre, pos

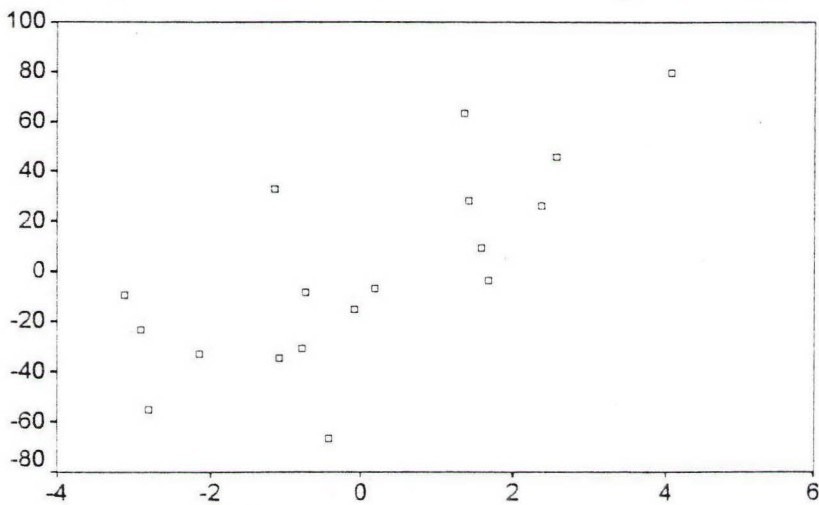


of years since last cut

seedlings/acre, post cut, per decade, age 3-12

Partial Regression Plot

Dependent Variable: # seedlings/acre, post



% of clay in soil

Regression - Seedling Response on TES 582, Productive Basalt Soils

Descriptive Statistics

	Mean	Std. Deviation	N
# seedlings/acre, post cut, per decade, age 3-12, not under canopy	11.8867	9.7976	15
% MEAN CANOPY FOR STAND	.3100	.1377	15
% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	5.8133	2.5698	15
% total sand in soil	45.9333	5.7005	15
log, # of years since last cut	1.2427	.3270	15

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.838 ^a	.702	.583	6.3277	1.919

a. Predictors: (Constant), log, # of years since last cut, % total sand in soil, % GROUND COVERED BY DEAD & DOWN <25CM DIAMETER, % MEAN CANOPY FOR STAND

b. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	943.487	4	235.872	5.891	.011 ^a
	Residual	400.402	10	40.040		
	Total	1343.889	14			

a. Predictors: (Constant), log, # of years since last cut, % total sand in soil, % GROUND COVERED BY DEAD & DOWN <25CM DIAMETER, % MEAN CANOPY FOR STAND

b. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	-1.550	17.331		-.089	.931
	% MEAN CANOPY FOR STAND	37.518	16.235	.527	2.311	.043
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	-2.766	.823	-.725	-3.362	.007
	% total sand in soil	.880	.306	.512	2.880	.016
	log, # of years since last cut	-18.133	6.039	-.605	-3.003	.013

Coefficients^a

Model		95% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	-40.166	37.067		
	% MEAN CANOPY FOR STAND	1.344	73.692	.572	1.748
	% GROUND COVERED BY DEAD & DOWN <25CM DIAMETER	-4.599	-.933	.640	1.563
	% total sand in soil	.199	1.561	.943	1.061
	log, # of years since last cut	-31.588	-4.678	.733	1.363

a. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

Residuals Statistics^a

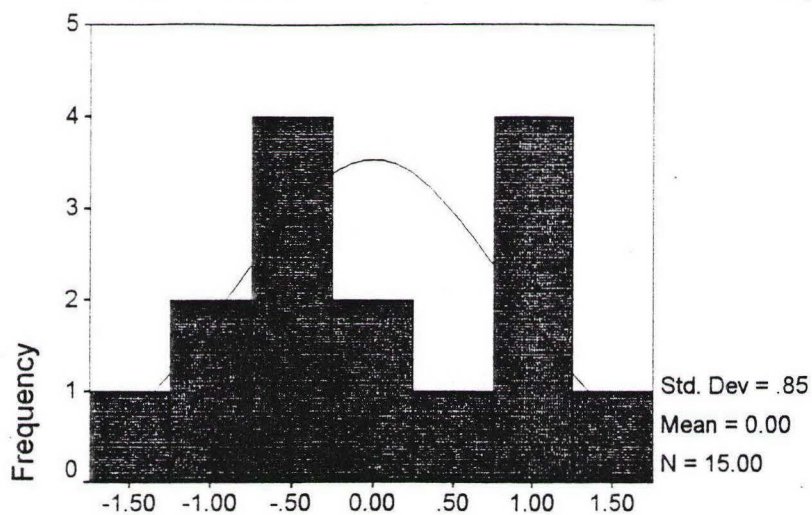
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	-.8704	23.6504	11.8867	8.2093	15
Residual	-9.0171	8.0596	-6.99E-15	5.3479	15
Std. Predicted Value	-1.554	1.433	.000	1.000	15
Std. Residual	-1.425	1.274	.000	.845	15

a. Dependent Variable: # seedlings/acre, post cut, per decade, age 3-12, not under canopy

Charts

Histogram

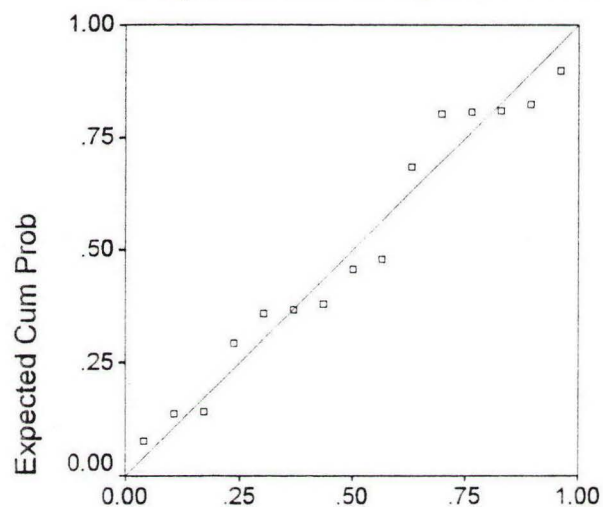
Dependent Variable: # seedlings/acre, post c



Regression Standardized Residual

Normal P-P Plot of Regression Sta

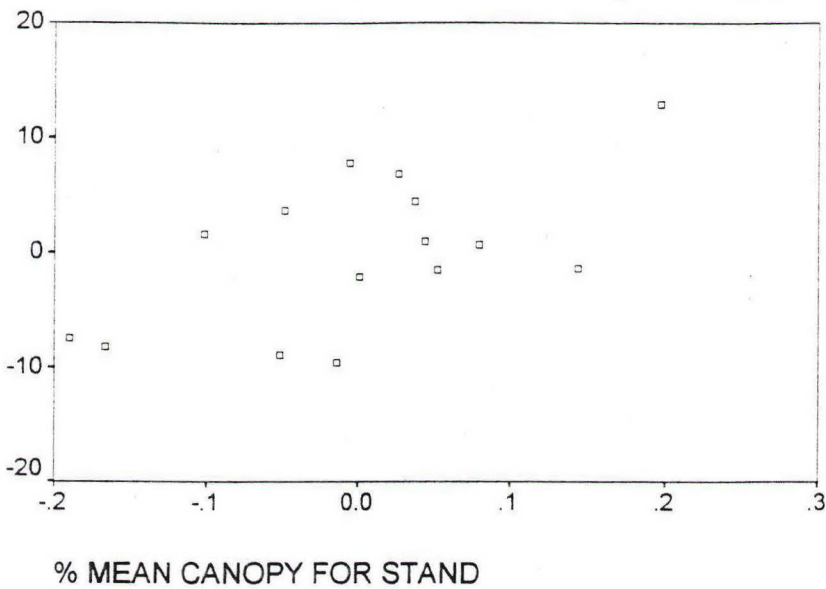
Dependent Variable: # seedlings/a



Observed Cum Prob

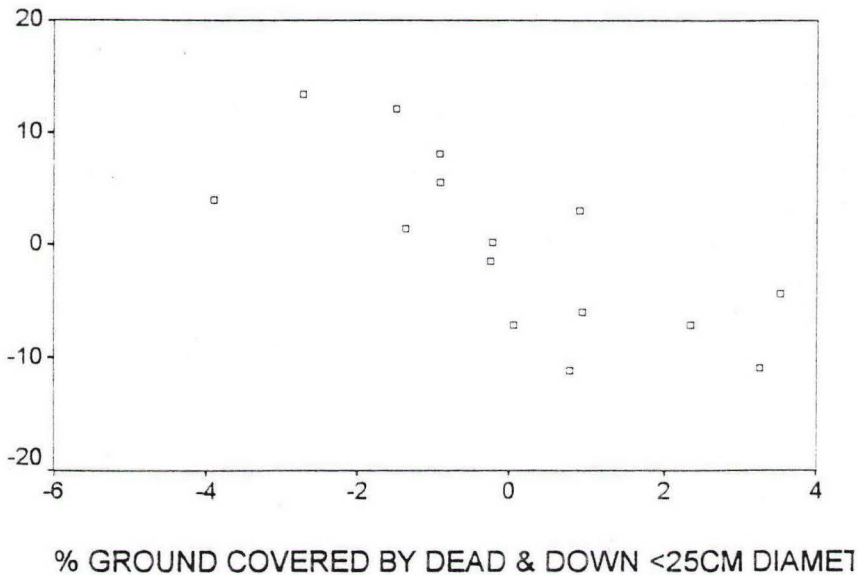
seedlings/acre, post cut, per decade, age 3-12

Partial Regression Plot
Dependent Variable: # seedlings/acre, post



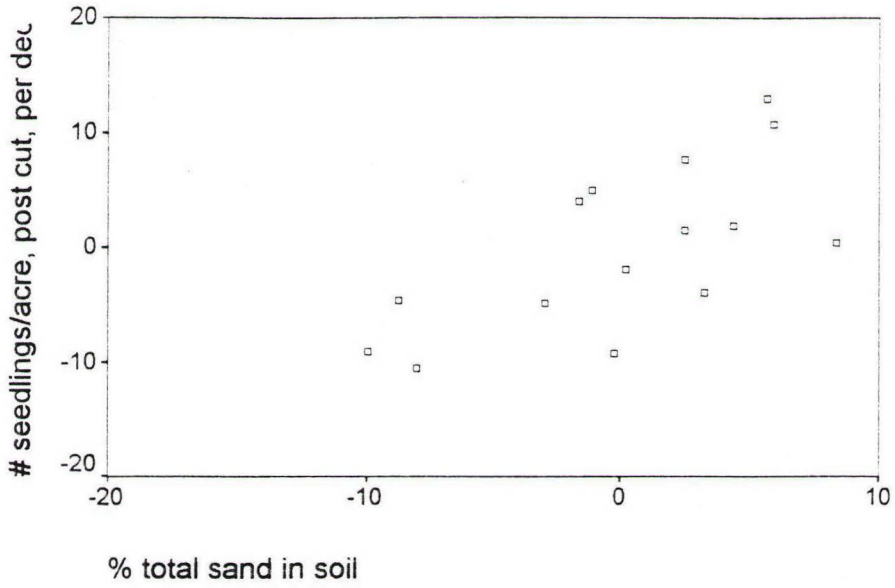
seedlings/acre, post cut, per decade, age 3-12

Partial Regression Plot
Dependent Variable: # seedlings/acre, post



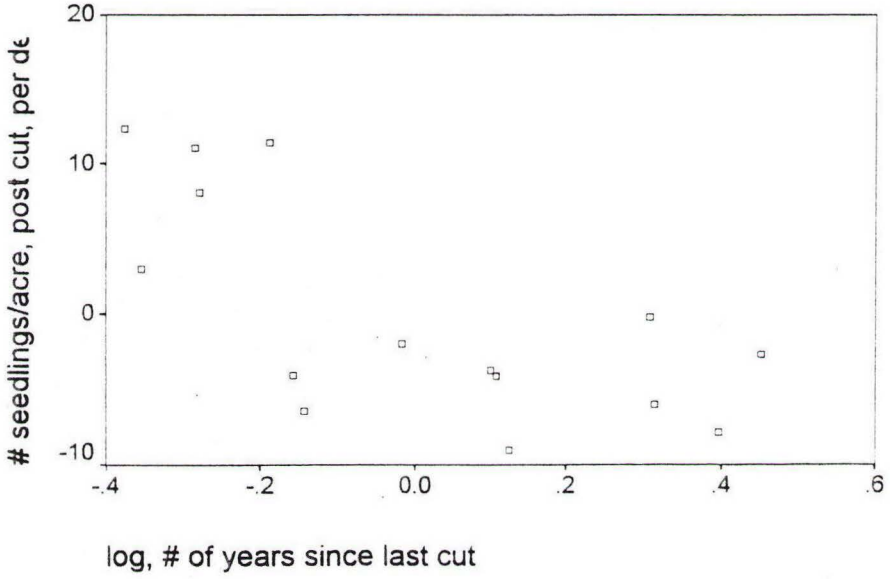
Partial Regression Plot

Dependent Variable: # seedlings/acre, post



Partial Regression Plot

Dependent Variable: # seedlings/acre, post



Regression - Predicted vs. Observed Seedling Response on Limestone Soils - TES 546 & 650

Descriptive Statistics

	Mean	Std. Deviation	N
predicted # seedlings/acre, no canopy, on limestone soils	66.9084	69.4335	18
# seedlings/acre, post cut, per decade, age 3-12, not under canopy	66.9467	74.5155	18

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.932 ^a	.868	.860	25.9943	1.369

- a. Predictors: (Constant), # seedlings/acre, post cut, per decade, age 3-12, not under canopy
- b. Dependent Variable: predicted # seedlings/acre, no canopy, on limestone soils

ANOVA^b

del	Sum of Squares	df	Mean Square	F	Sig.
Regression	71145.904	1	71145.904	105.291	.000 ^a
Residual	10811.267	16	675.704		
Total	81957.171	17			

- a. Predictors: (Constant), # seedlings/acre, post cut, per decade, age 3-12, not under canopy
- b. Dependent Variable: predicted # seedlings/acre, no canopy, on limestone soils

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	8.787	8.344		1.053	.308
	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	.868	.085	.932	10.261	.000

Coefficients^a

Model		95% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	-8.901	26.476		
	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	.689	1.048	1.000	1.000

a. Dependent Variable: predicted # seedlings/acre, no canopy, on limestone soils

Residuals Statistics^a

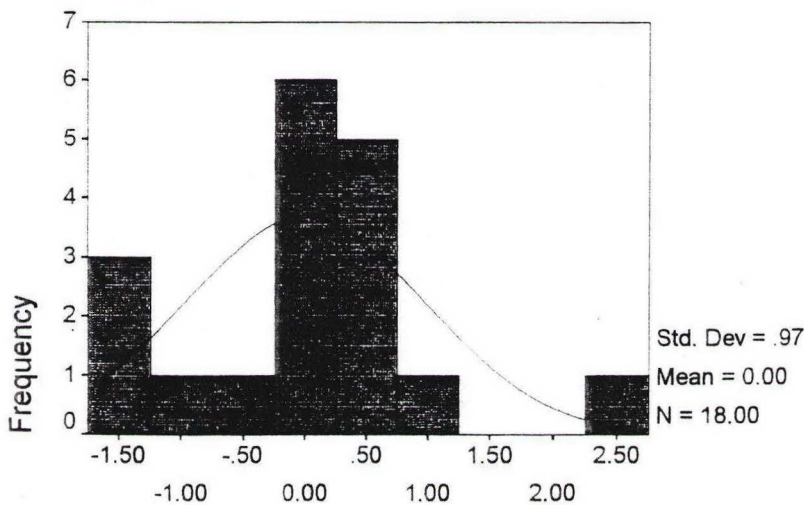
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	8.7874	210.2024	66.9084	64.6920	18
Residual	-38.7253	69.6324	-1.14E-14	25.2182	18
Std. Predicted Value	-.898	2.215	.000	1.000	18
Std. Residual	-1.490	2.679	.000	.970	18

a. Dependent Variable: predicted # seedlings/acre, no canopy, on limestone soils

Charts

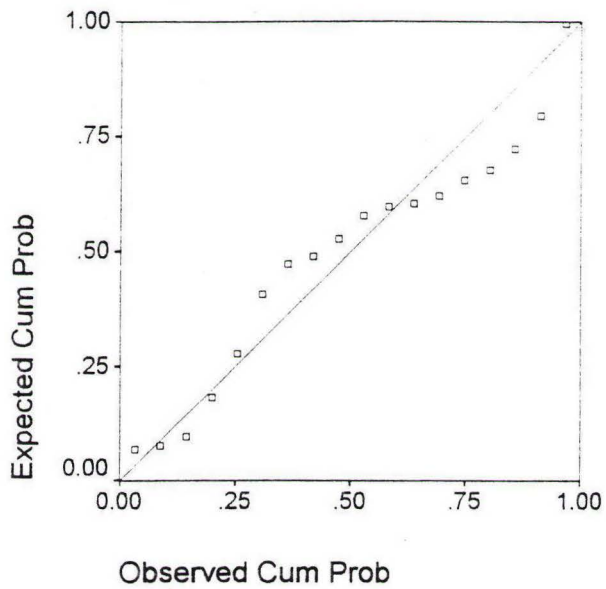
Histogram

Dependent Variable: predicted # seedlings/a

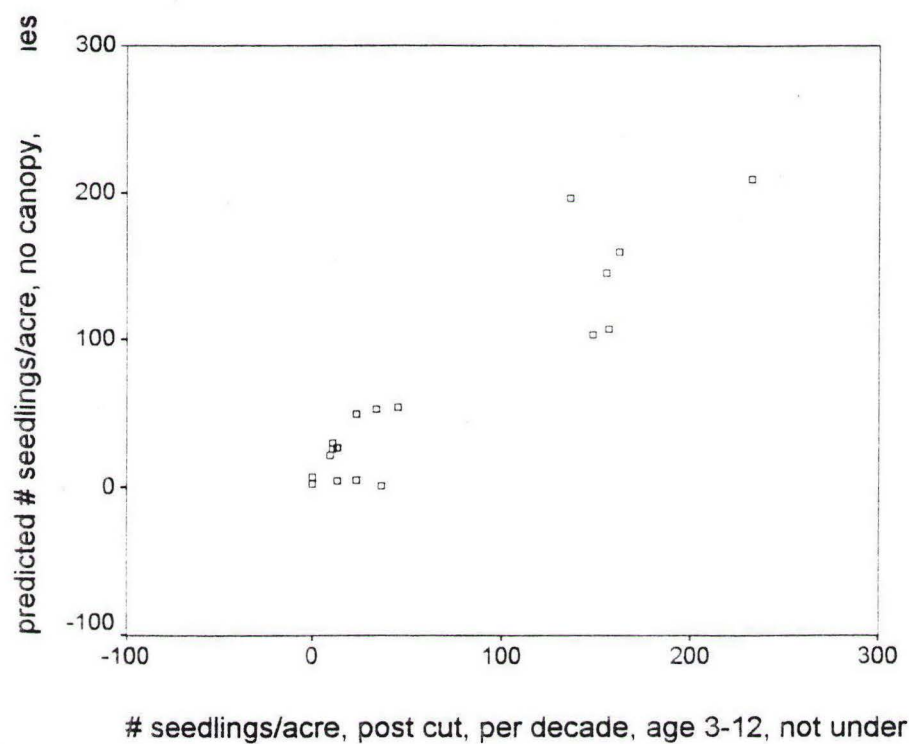


Normal P-P Plot of Regression Sta

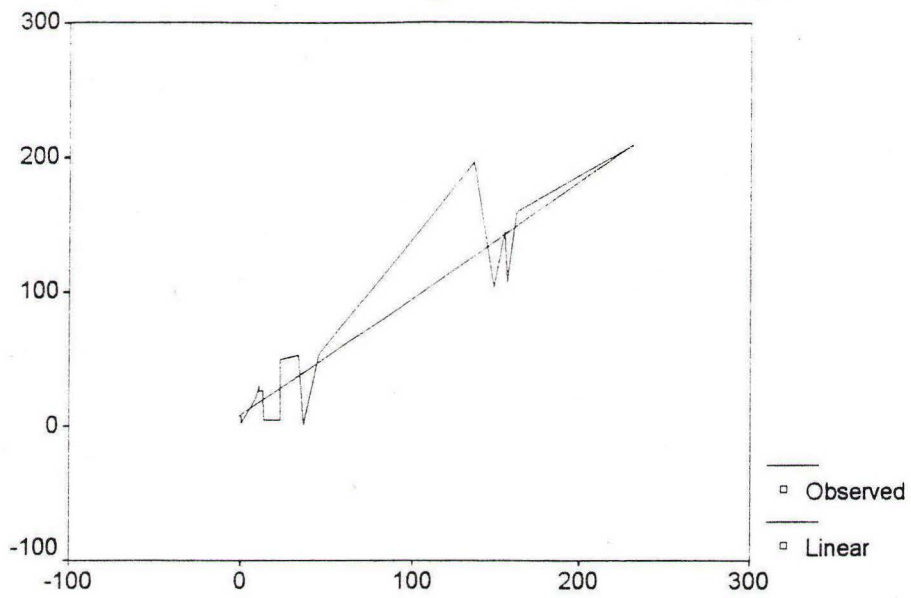
Dependent Variable: predicted # seedlings/acre, no canopy



Graph



predicted # seedlings/acre, no canopy, on lime



seedlings/acre, post cut, per decade, age 3-12, not under canopy

Regression - Predicted vs. Observed Seedling Response TES 582 Soils

Descriptive Statistics

	Mean	Std. Deviation	N
predicted # seedlings, TES 582	12.8000	7.6925	14
# seedlings/acre, post cut, per decade, age 3-12, not under canopy	12.4121	9.9456	14

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.848 ^a	.718	.695	4.2485	1.819

a. Predictors: (Constant), # seedlings/acre, post cut, per decade, age 3-12, not under canopy

b. Dependent Variable: predicted # seedlings, TES 582

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	552.673	1	552.673	30.619	.000 ^a
	Residual	216.602	12	18.050		
	Total	769.275	13			

a. Predictors: (Constant), # seedlings/acre, post cut, per decade, age 3-12, not under canopy

b. Dependent Variable: predicted # seedlings, TES 582

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	4.663	1.858		2.510	.027
	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	.656	.118	.848	5.533	.000

Coefficients^a

Model		95% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	.615	8.711		
	# seedlings/acre, post cut, per decade, age 3-12, not under canopy	.397	.914	1.000	1.000

a. Dependent Variable: predicted # seedlings, TES 582

Residuals Statistics^a

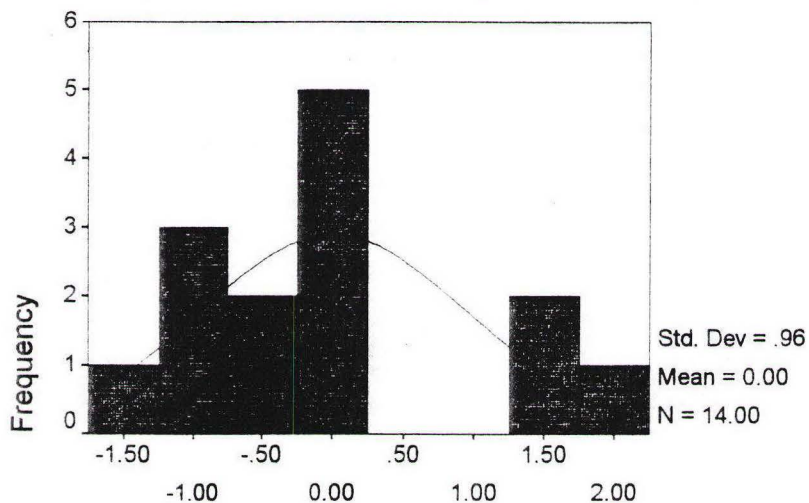
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	5.6527	25.4514	12.8000	6.5202	14
Residual	-6.0057	7.7164	-8.25E-16	4.0819	14
Std. Predicted Value	-1.096	1.940	.000	1.000	14
Std. Residual	-1.414	1.816	.000	.961	14

a. Dependent Variable: predicted # seedlings, TES 582

Charts

Histogram

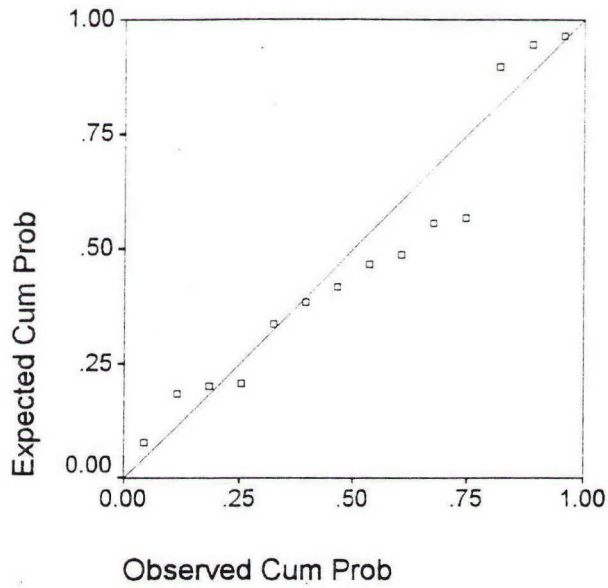
Dependent Variable: predicted # seedlings, 1



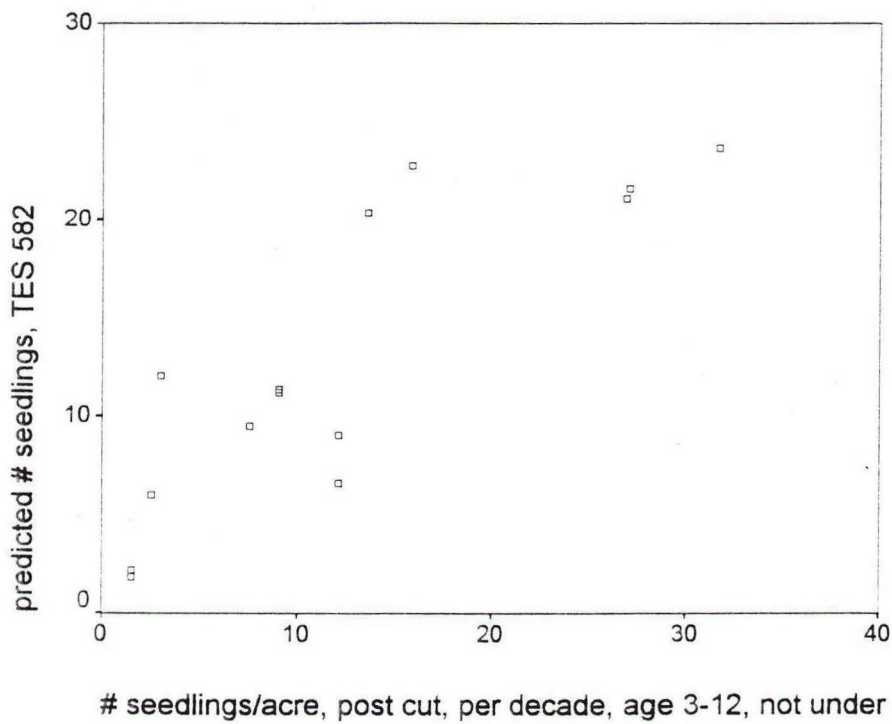
Regression Standardized Residual

Normal P-P Plot of Regression Sta

Dependent Variable: predicted # se



Graph

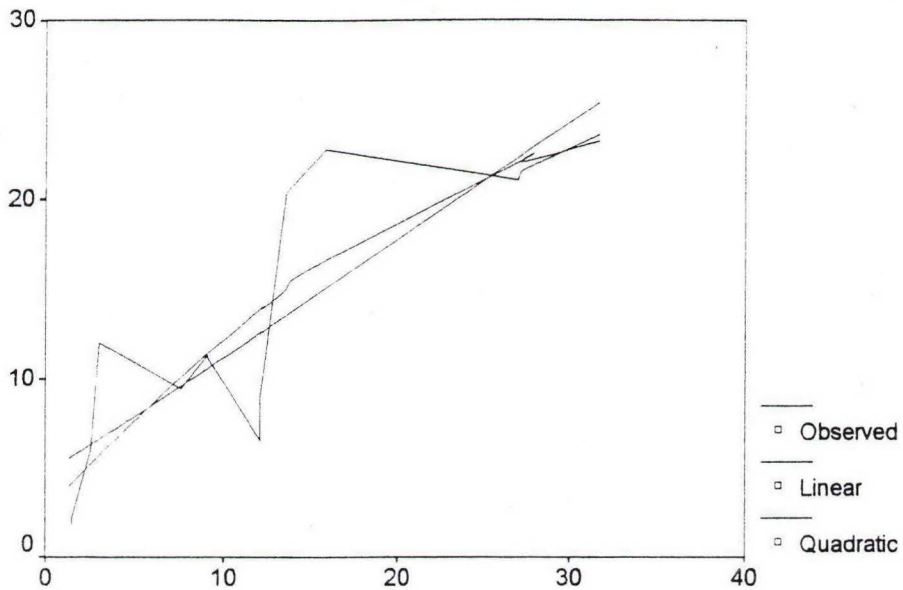


Independent: SDLGNOCA

endent Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
------------	-----	------	---	------	----	----	----

PRED582	LIN	.718	12	30.62	.000	4.6628	.6556	
PRED582	QUA	.746	11	16.17	.001	2.4531	1.1275	-.0148

predicted # seedlings, TES 582



seedlings/acre, post cut, per decade, age 3-12, not under canopy

3. Soil Compaction and Seedling Density:

Soil conditions and impacts of grazing may be preventing adequate and successful natural regeneration of ponderosa pine on some stands in the Coconino National Forest. Limestone fine sandy loams and basalt clay loams are prevalent across the Forest, and they comprise the four TES soil types in this study. Both soils are fine in texture and thus prone to compaction.

Logging and grazing can cause compaction under some conditions (Froelich 1986). Extensive tractor logging and machine piling of slash occurred across the Coconino NF from 1960-1990. Forest-wide, elk graze annually and cattle graze either annually or biannually. Grazing by cattle has been shown to increase soil bulk density on a number of soil types across the western U.S. The increase appears to be due to both trampling and to a reduction in robust grass roots and soil organic matter that loosen soil.

To look at the relationship between soil compaction and seedling density, bulk density at the 0-15cm depth was derived at 3-6 random points on each study stand, for a total of 180 bulk density values. The location of each bulk density sample was recorded. Bulk densities were also obtained at 12 random points on each of two unlogged and rarely grazed areas; these serve as undisturbed reference sites. One site is at the Fort Valley Experimental Forest on TES 582 basalt soil, and the other site is on the Blue Ridge Ranger District on TES 546 limestone soil.

The National Soil Cooperative Survey (NSCS) considers a soil to be impaired (moderately to severely compacted) if its bulk density is 20% higher than the bulk density of an undisturbed site with comparable soil type. Some soil scientists who were consulted on this aspect of the study classify a soil as impaired if its bulk density is 15% higher than a comparable undisturbed soil. The 20% value is used in this study.

The mean soil bulk density obtained for this study at the undisturbed site with basalt clay loams (Ft. Valley Experimental Forest) is 0.99gr/cc. On limestone fine sandy loam soils, the undisturbed site (Blue Ridge Ranger Station) mean bulk density is 1.11gr/cc. The range of values among the 12 samples at each site is within 20% of the mean. These mean values are very close to the undisturbed values obtained for the same soil types in a 1954 NSCS soil survey in northern Arizona, which found 1.00gr/cc for basalt clay loam and 1.10gr/cc for limestone fine sandy loam.

Sample points on the 47 study stands were classified by relative location:

- * On what is obviously an old skid trail
- * In any opening other than a skid trail, ie. not under tree canopy
- * Under tree canopy
- * 1m from the stem of a 9-12 year old pipo seedling (if the random point fell within 15m of the seedling)

On the **attached two charts "Bulk Densities Undisturbed Reference Values"**, the solid horizontal reference lines indicate the undisturbed soil reference values obtained in the 1954 NSCS survey. The dotted horizontal reference lines indicate the value at which these soils are considered impaired. Thus, impairment on limestone soils begins at 1.32gr/cc, while impairment on basalt soils begins at 1.20gr/cc. In this study, impaired soils were found on:

- * 65% of skid trails
- * 58% of openings
- * 37% of area under tree canopy
- * 15% of area 1m from established seedlings

Differences in bulk densities were within stands, not among stands, as can be seen in the result of a paired t-test by stands:

- * Within Stand BD in Openings Differ from BD by Seedlings P=.000
- * Within Stand BD on Skid Trails Differ from BD by Seedlings P=.001

Is 1m from the stem of a seedling close enough to the stem that the seedling roots are infringing upon the soil core; ie. seedling roots are loosening the soil and causing the lower bulk densities? Among all study stands, the highest bulk density near seedlings is 1.34gr/cc. The range of bulk densities in openings is 0.93-1.97gr/cc. Thus, the soil near some seedlings is more compacted than the soil found in some openings, indicating that seedlings are selecting for areas with low bulk density, not causing areas of low bulk density.

In the following Pearson correlations, bulk densities (BD) are adjusted for soil type, so all soil types have the same bulk densities relative to degree of soil compaction. Since sample sizes are small (3-6) for each stand, correlations are for all study stands combined. Stands with higher mean bulk densities in openings have less grass, fewer seedlings not under canopy per seed tree, and fewer seedlings growing in bare soil.

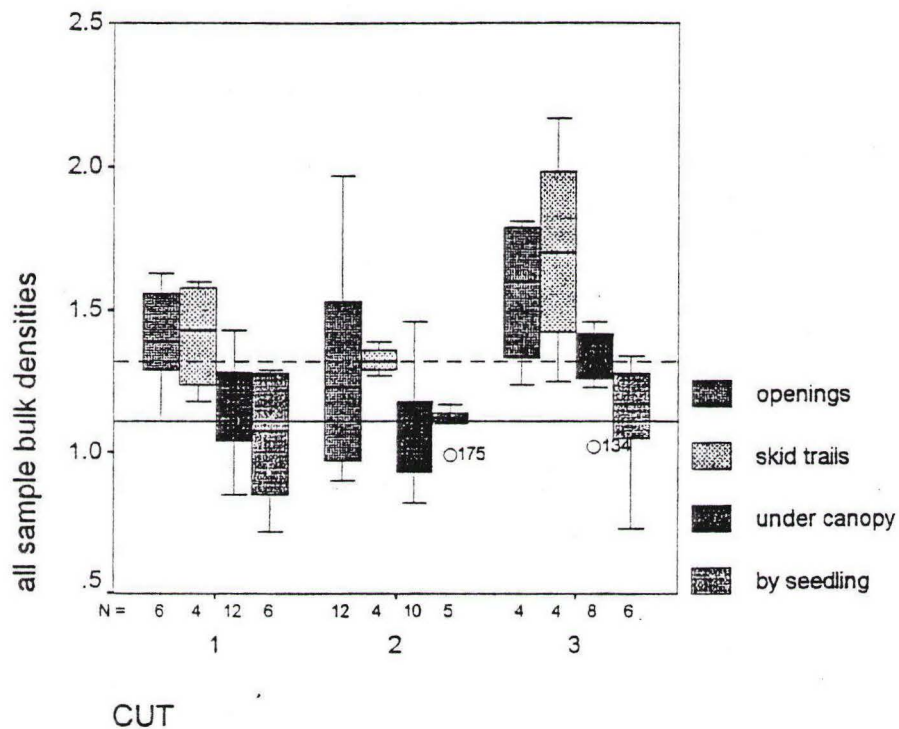
	<u>Pearson Corr.</u>	<u>Sign.(2-tailed)</u>
BD in openings - % ground in grasses	-.366	P=.012
BD in openings - # seedlings no canopy/ # seed trees	-.261	P=.099
BD in openings - % seedlings in bare soil	-.221	P=.139

No significant difference is seen between bulk densities on DOG stands, which haven't been logged since 1975, and bulk densities on those SH stands that were logged after 1985. Needle litter is slowly decomposing and incorporating into the soil. Under tree canopies, the top 5-15cm of soil generally contains large amounts of decomposing needle litter and is thus low in bulk density. At depths below the mix of soil and decomposed needles, the soil is usually comprised of heavily compacted clay.

Bulk Densities gr/cc Limestone Fine Sandy Loams

Undisturbed reference value = 1.11

1. Aired soil value = 1.32 (dotted line)

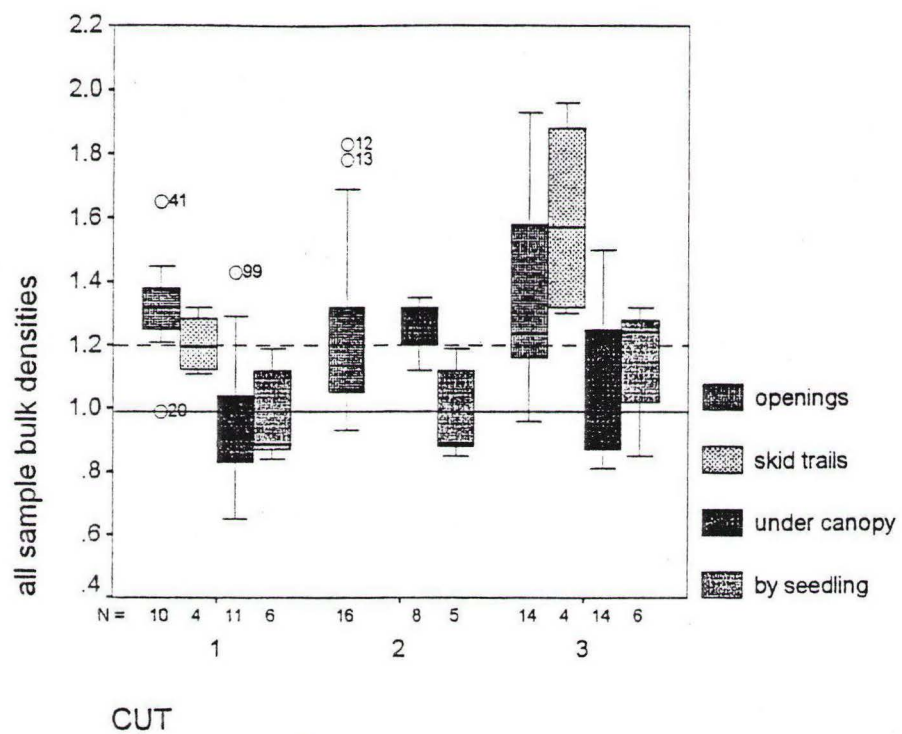


Cut: 1=not cut since 1975

2=shelterwood cut since 1985

3=commercial thinned since 1985

Bulk Densities gr/cc Basalt Clay Loam Soils
 Undisturbed reference value = 0.99
 Aired soil value = 1.20 (dotted line)



Cut: 1=not cut since 1975
 2=shelterwood cut since 1985
 3= commercial thinned since 1985

4. Soil Compaction and Seedling Root/Shoot Growth:

Several studies in the Pacific Northwest and the southeastern U.S. of ponderosa pine and other conifer species have found increases in bulk densities of 13-43% on skid trails after logging, and comparative declines in volume growth of seedlings and saplings of 18-69% on skid trails (Helms & Hipkin 1986). A greenhouse experiment on other pine species, (Halverson and Zisa 1982) indicates that seedling root penetration depth is highly correlated with soil compaction. Root depth is of critical importance in the establishment of ponderosa pine seedlings; their roots generally need to extend to a depth of approximately 23cm between July/August germination and the ensuing winter to survive frost heaving, competition for water with grasses, and extended periods between precipitation events (Pearson 1942).

The effect of soil compaction within the study stands on pine seedling root and shoot length was determined in a 2x5 factorial fixed effects greenhouse experiment in which root and shoot length were compared among pine seedlings germinated in two soil types and five soil bulk densities.

Ponderosa pine seeds were collected in October, 2001, from one tree near Flagstaff. A second seed tree was in the vicinity, so a few seeds may be from two trees. The seeds were floated, sterilized, and then refrigerated. In May, 2002, soil from 0-25cm depth was collected from 10 randomly selected locations on each of two of the 47 study stands – one stand is developing old growth with good regeneration on TES 582 (productive basalt) soil; the other stand is developing old growth with good regeneration on TES 546 (limestone) soil.

Soils from each stand were thoroughly mixed, sieved to 5mm, and oven-dried. White seedling pots 65mm in diameter and 25cm deep were filled with soil in 1cm increments and compacted to one of five bulk densities. Prior to filling the pots, 2mm screening was attached to the drain holes; this permitted water to drain with no loss of soil.

Twenty pots each were filled with the prepared limestone soil at the following bulk densities: 1.0gr/cc 1.1gr/cc 1.2gr/cc 1.3gr/cc 1.4gr/cc. Ten pots were filled with uncompacted limestone soil (approximately 1.0gr/cc) to serve as controls. The same number of pots were filled with the prepared basalt soil at the same bulk densities (uncompacted basalt soil was at approximately 0.9gr/cc).

On June 13, the 220 pots were placed in the NAU Greenhouse, and two seeds were planted in each pot. Pots were arranged randomly; they were checked daily and watered as needed to keep soils moist but not saturated. Pots were thinned to one seedling once the terminal growth leaders began to elongate. Germination began on June 21 and continued for three weeks. Ninety-four of the pots had germinated by June 26, and only these were used for the study.

Neither soil type nor bulk density had any effect on which pots had seedlings that germinated late or failed to germinate. Any relationship between seedling development

and germination date was invalidated once the maximum daily temperature in the greenhouse exceeded 84°F. On that day, development of seedlings which had germinated on June 26 caught up to those which germinated on June 21.

On July 28, seedling roots were nearing the bottom of some of the control (uncompacted) pots, and the experiment was stopped. Pots were cut open lengthwise and soil was gently washed from the roots. Root and shoot lengths were determined immediately.

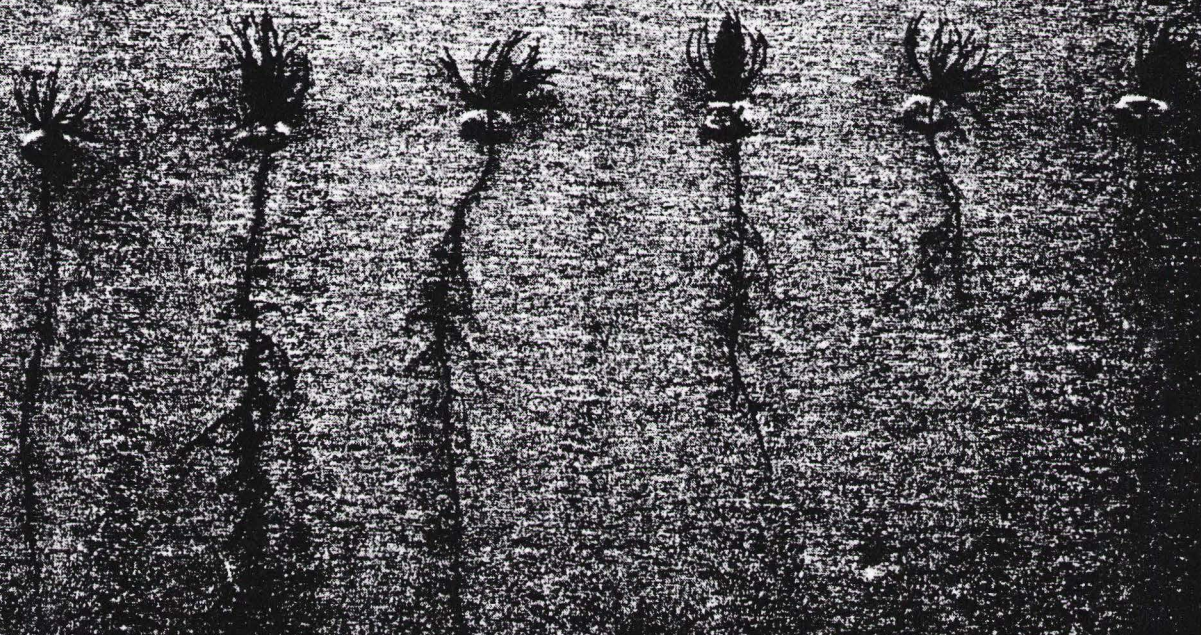
Increasing bulk density affects both shoot and root length of ponderosa pine seedlings. The marked decrease in root length at bulk densities of 1.2-1.3 gr/cc correlates well with the results of the soil bulk density survey described above. In that survey, nearly all bulk densities 1m from 9-12 year old seedlings were below 1.3 gr/cc, and few were as high as 1.2 gr/cc. Bulk density appears to more greatly affect seedling root and shoot length than soil type. See the **attached photo and charts "Pearson Correlations and "Univariate Analysis of Variance"**.

A dense, robust grass community may alleviate compaction over time. Growing roots break up the soil, then die to become soil organic matter. Dead grass stems decompose on the soil surface and, if not removed by ungulates or fire, over time may be incorporated into the soil. High tree densities and their resulting needle litter which are found in some areas of the Forest, and continuous grazing by cattle and elk Forest-wide, may both be preventing the development of the abundant and vigorous grasses needed to reduce compaction.

Will prescribed fire and/or thinning help alleviate compaction on the Coconino NF? Perhaps, if grazing also is significantly reduced to thus allow grass density and grass vigor to increase. If levels of grazing are not decreased, then the loss of needle litter from fire and pressure on the ground surface from thinning operations could make compaction worse.

limestone

C 1.0 1.1 1.2 1.3 1.4



basalt

C 1.0 1.1 1.2 1.3 1.4



Pearson Correlations - bulk density and seedling root length

Correlations

		bulk density in gr/cc	root length in mm
bulk density in gr/cc	Pearson Correlation	1.000	-.757**
	Sig. (2-tailed)	.	.000
	N	94	94
root length in mm	Pearson Correlation	-.757**	1.000
	Sig. (2-tailed)	.000	.
	N	94	94

** . Correlation is significant at the 0.01 level (2-tailed).

Univariate Analysis of Variance - seedling root length

etween-Subjects Factors

		N
soil type basalt =	1	52
1 limestone =	2	42
bulk density in	.90	7
gr/cc	1.00	23
	1.10	20
	1.20	17
	1.30	17
	1.40	10

Tests of Between-Subjects Effects

Dependent Variable: root length in mm

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	251462.65 ^a	10	25146.265	17.261	.000
Intercept	1669811.0	1	1669811.0	1146.201	.000
SOILTYPE	935.190	1	935.190	.642	.425
BULKDENS	197782.54	5	39556.509	27.153	.000
TYPE * BULKDENS	25684.041	4	6421.010	4.408	.003
Error	120916.21	83	1456.822		
Total	3081504.0	94			
Corrected Total	372378.85	93			

a. R Squared = .675 (Adjusted R Squared = .636)

soil type basalt = 1 limestone = 2 * bulk density in gr/cc

Dependent Variable: root length in mm

				95% Confidence Interval		
				Interval		
soil type basalt = 1 limestone = 2		bulk density in gr/cc	Mean	Std. Error	Lower Bound	Upper Bound
1	.90		222.429	14.426	193.735	251.122
	1.00		227.364	11.508	204.474	250.253
	1.10		173.333	12.723	148.028	198.638
	1.20		179.556	12.723	154.250	204.861
	1.30		121.000	10.201	100.711	141.289
	1.40		58.500	26.989	4.820	112.180
2	.90		^a	.	.	.
	1.00		209.167 ^b	11.018	187.252	231.082
	1.10		217.273 ^b	11.508	194.383	240.162
	1.20		138.750 ^b	13.495	111.910	165.590
	1.30		68.000 ^b	22.036	24.170	111.830
	1.40		87.375 ^b	13.495	60.535	114.215

a. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

b. Based on modified population marginal mean.

Multiple Comparisons

Dependent Variable: root length in mm
 Tukey HSD

		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
(I) bulk density in gr/cc	(J) bulk density in gr/cc				Lower Bound	Upper Bound
.90	1.00	4.56	16.48	1.000	-43.51	52.63
	1.10	24.93	16.76	.673	-23.97	73.83
	1.20	62.08*	17.14	.006	12.07	112.08
	1.30	110.78*	17.14	.000	60.77	160.79
	1.40	140.83*	18.81	.000	85.95	195.70
1.00	.90	-4.56	16.48	1.000	-52.63	43.51
	1.10	20.37	11.67	.506	-13.68	54.41
	1.20	57.52*	12.21	.000	21.90	93.13
	1.30	106.22*	12.21	.000	70.61	141.84
	1.40	136.27*	14.46	.000	94.09	178.45
1.10	.90	-24.93	16.76	.673	-73.83	23.97
	1.00	-20.37	11.67	.506	-54.41	13.68
	1.20	37.15*	12.59	.046	.41	73.88
	1.30	85.85*	12.59	.000	49.12	122.59
	1.40	115.90*	14.78	.000	72.77	159.03
1.20	.90	-62.08*	17.14	.006	-112.08	-12.07
	1.00	-57.52*	12.21	.000	-93.13	-21.90
	1.10	-37.15*	12.59	.046	-73.88	-.41
	1.30	48.71*	13.09	.005	10.51	86.90
	1.40	78.75*	15.21	.000	34.38	123.13
1.30	.90	-110.78*	17.14	.000	-160.79	-60.77
	1.00	-106.22*	12.21	.000	-141.84	-70.61
	1.10	-85.85*	12.59	.000	-122.59	-49.12
	1.20	-48.71*	13.09	.005	-86.90	-10.51
	1.40	30.05	15.21	.365	-14.33	74.42
1.40	.90	-140.83*	18.81	.000	-195.70	-85.95
	1.00	-136.27*	14.46	.000	-178.45	-94.09
	1.10	-115.90*	14.78	.000	-159.03	-72.77
	1.20	-78.75*	15.21	.000	-123.13	-34.38
	1.30	-30.05	15.21	.365	-74.42	14.33

Based on observed means.

*. The mean difference is significant at the .05 level.

Correlations - bulk density and seedling shoot length

Correlations

		bulk density in gr/cc	shoot length in mm
bulk density in gr/cc	Pearson Correlation	1.000	-.255*
	Sig. (2-tailed)	.	.013
	N	94	94
shoot length in mm	Pearson Correlation	-.255*	1.000
	Sig. (2-tailed)	.013	.
	N	94	94

*. Correlation is significant at the 0.05 level (2-tailed).

Univariate Analysis of Variance - seedling shoot length

Between-Subjects Factors

		N
soil type basalt = 1	1	52
1 limestone = 2	2	42
bulk density in gr/cc	.90	7
	1.00	23
	1.10	20
	1.20	17
	1.30	17
	1.40	10

Tests of Between-Subjects Effects

Dependent Variable: shoot length in mm

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2603.016 ^a	10	260.302	3.870	.000
Intercept	359364.86	1	359364.86	5343.104	.000
SOILTYPE	809.776	1	809.776	12.040	.001
BULKDENS	1120.334	5	224.067	3.331	.009
SOILTYPE * BULKDENS	311.545	4	77.886	1.158	.335
Error	5582.389	83	67.258		
Total	515556.00	94			
Corrected Total	8185.404	93			

a. R Squared = .318 (Adjusted R Squared = .236)

soil type basalt = 1 limestone = 2 * bulk density in gr/cc

Dependent Variable: shoot length in mm

		Mean	Std. Error	95% Confidence Interval	
soil type basalt = 1 limestone = 2	bulk density in gr/cc			Lower Bound	Upper Bound
1	.90	84.143	3.100	77.978	90.308
	1.00	77.909	2.473	72.991	82.827
	1.10	71.222	2.734	65.785	76.659
	1.20	79.778	2.734	74.341	85.215
	1.30	74.500	2.192	70.141	78.859
	1.40	73.000	5.799	61.466	84.534
2	.90	^a	.	.	.
	1.00	73.500 ^b	2.367	68.791	78.209
	1.10	67.818 ^b	2.473	62.900	72.736
	1.20	68.250 ^b	2.900	62.483	74.017
	1.30	61.000 ^b	4.735	51.582	70.418
	1.40	69.375 ^b	2.900	63.608	75.142

a. This level combination of factors is not observed, thus the corresponding population marginal mean is not estimable.

b. Based on modified population marginal mean.

Multiple Comparisons

Dependent Variable: shoot length in mm

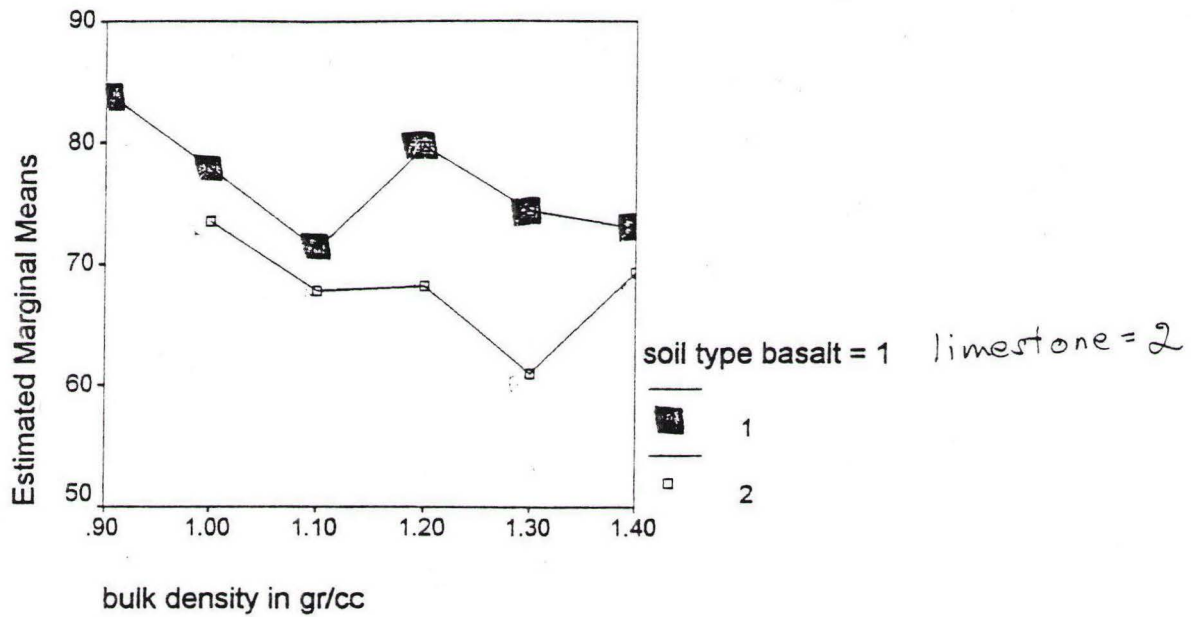
Tukey HSD

		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
(I) bulk density in gr/cc	(J) bulk density in gr/cc				Lower Bound	Upper Bound
.90	1.00	8.53	3.54	.165	-1.79	18.86
	1.10	14.79*	3.60	.001	4.29	25.30
	1.20	9.79	3.68	.095	-.95	20.53
	1.30	12.03*	3.68	.019	1.28	22.77
	1.40	14.04*	4.04	.010	2.25	25.83
1.00	.90	-8.53	3.54	.165	-18.86	1.79
	1.10	6.26	2.51	.137	-1.06	13.57
	1.20	1.26	2.62	.997	-6.40	8.91
	1.30	3.49	2.62	.767	-4.16	11.14
	1.40	5.51	3.11	.488	-3.55	14.57
1.10	.90	-14.79*	3.60	.001	-25.30	-4.29
	1.00	-6.26	2.51	.137	-13.57	1.06
	1.20	-5.00	2.71	.441	-12.90	2.89
	1.30	-2.77	2.71	.909	-10.66	5.13
	1.40	-.75	3.18	1.000	-10.02	8.52
1.20	.90	-9.79	3.68	.095	-20.53	.95
	1.00	-1.26	2.62	.997	-8.91	6.40
	1.10	5.00	2.71	.441	-2.89	12.90
	1.30	2.24	2.81	.968	-5.97	10.44
	1.40	4.25	3.27	.784	-5.28	13.79
1.30	.90	-12.03*	3.68	.019	-22.77	-1.28
	1.00	-3.49	2.62	.767	-11.14	4.16
	1.10	2.77	2.71	.909	-5.13	10.66
	1.20	-2.24	2.81	.968	-10.44	5.97
	1.40	2.02	3.27	.989	-7.52	11.55
1.40	.90	-14.04*	4.04	.010	-25.83	-2.25
	1.00	-5.51	3.11	.488	-14.57	3.55
	1.10	.75	3.18	1.000	-8.52	10.02
	1.20	-4.25	3.27	.784	-13.79	5.28
	1.30	-2.02	3.27	.989	-11.55	7.52

Based on observed means.

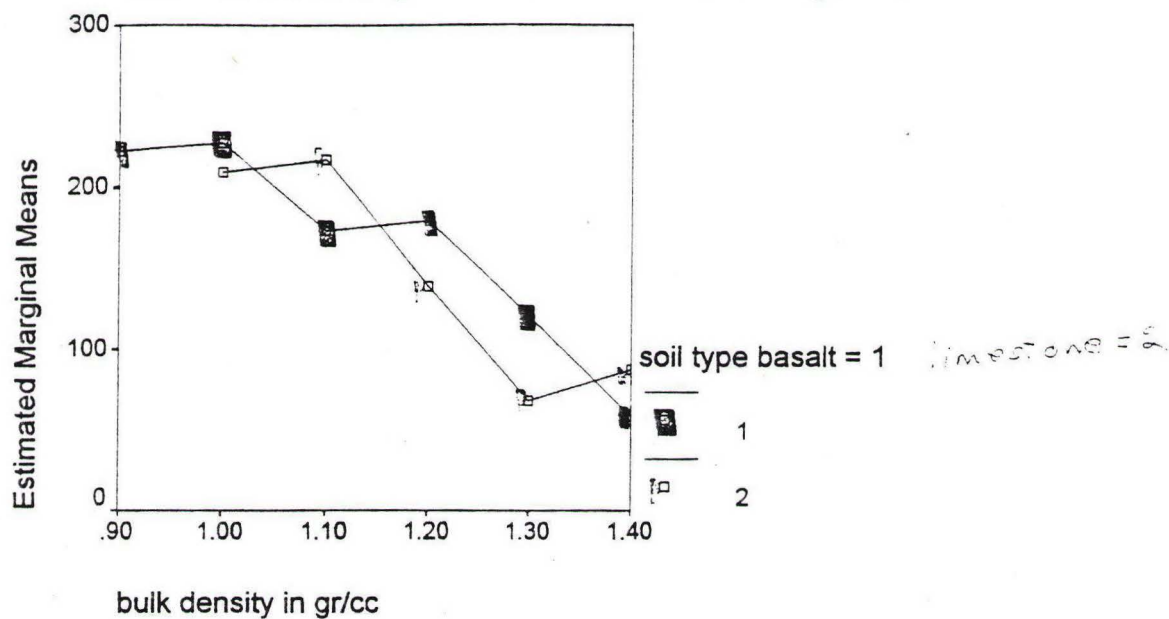
*. The mean difference is significant at the .05 level.

Estimated Marginal Means of shoot length in mm



Non-estimable means are not plotted

Estimated Marginal Means of root length in *maize*



Non-estimable means are not plotted

5. Seedling Mortality from Prescribed Fire and Cohort Competition:

Walk through surveys were conducted across five areas lying on the study soil types shortly after they were treated with prescribed burns. One of these areas includes one of the 47 study stands. Seedling mortality was recorded, both by seedling size and location.

Three areas on the Peaks Ranger District were burned in Fall, 2000. In Spring and Summer, 2001, two areas south of Mormon Lake were also burned. Within these five areas, mortality of seedlings <1.3m tall ranged from 65-85%, with average mortality of 78%. The three Peaks burns were in even-aged poles with 60-80sq ft basal area, and the two burns south of Mormon Lake were in poles and saplings with 60-110sq ft basal area. Fuel loads were high on all areas. All five burns were hot, and nearly all dead and down woody material in the path of fire was consumed.

Mortality of seedlings <1.3m tall was 100% in the path of the five fires. On the burns south of Mormon Lake, no live seedlings <1.8m tall were found, other than those sheltered near tree trunks.

On the Peaks burns, mortality of seedlings 1.3-1.8m tall was 78% in the path of the fire 1-4 weeks after the burn. These areas were again surveyed in the summer of 2001 and over 80% of the surviving seedlings have died.

Seedlings across the study area may be found spatially dispersed or in dense cohort clumps. Thus, mortality from cohort competition for growing space must also be considered when estimating the number of seedlings that will survive to maturity.

Survival rates from cohort competition on each study stand were estimated on the study plot maps using average tree crown diameters at maturity. Diameters used were conservative for each site and allowed for considerable overlapping of crowns to simulate a clumpy spatial distribution. Based on these estimates, mean seedling survival rates from cohort competition for growing space is:

$$\text{DOG}=0.293 \quad \text{SH}=0.393 \quad \text{CT}=0.296$$

The above mean survival rates were used to predict the number of seedlings surviving cohort competition on each study stand. Predicted numbers of surviving seedlings were correlated with the number of surviving seedlings estimated via plot maps. Linear regression indicates these survival rates may be decent predictors of seedling survival from cohort competition (Adjusted R Square = 0.846). See the **attached "Regression – Predicted Number of Seedlings Surviving on All Stands"**.

Since the percent of ground burned and the intensity of the fire can vary greatly, depending on fuel loads and weather conditions, more monitoring is needed on future prescribed burns before any conclusions can be reached regarding seedling mortality rates from fire. Seedling mortality rates may be lower on areas frequently burned, which thus contain lighter fuel loads. However, prescribed burns on areas with dense grass (one

of the goals of restoration management) are likely to create tall enough flames to destroy all seedlings in the path of the fire. Whether fuel loads are high and comprised primarily of needle litter and slash, or whether fuel loads consist primarily of grass, seedling mortality from fire essentially appears to be a function of the percent of ground burned that is not under tree canopy.

Under current ecosystem conditions, seedling growth rates are so small that it is taking more than 25 years for nearly all seedlings to reach a height of 6ft, the height at which the majority may be able to survive ground fire. The average life span of southwestern ponderosa pine that reach maturity is 280 years (Swetnam; pers. comm.).

If the goal is to sustain stand density at 20-30 mature trees/acre, then 0.7-1.1 seedlings/acre/decade must survive to maturity. This seems like an easy target to attain, until one considers seedling mortality rates from each prescribed fire and from cohort competition.

Assume seedlings are exposed to two prescribed fires in 25 years:

$$\begin{aligned} 100 \text{ 3-12 year old seedlings/acre/decade} & \times 0.55 \text{ (\% seedlings not under canopy)} \\ & \times 0.22 \text{ (survival rate in 1st fire)} \\ & \times 0.22 \text{ (survival rate in 2nd fire)} \\ & \times 0.327 \text{ (mortality from cohort competition)} \\ & = 0.87 \text{ seedlings/acre/decade} \end{aligned}$$

In this study, only two of 28 stands on basalt soils (both DOG), and five of 19 stands on limestone soils have 100 or more seedlings/acre/decade.

Hopefully, restoration management will improve seedling densities and growth rates, and thus reduce the number of years needed for seedlings to outgrow ground fire. Keep in mind that growth rates in the first 20 years for var. *scopulorum* are inherently low (Rehfeldt 1993) but locally, seedlings can attain 20-30cm height growth under optimum conditions.

Regression - Predicted Number of Seedlings Surviving on All Stands

Descriptive Statistics

	Mean	Std. Deviation	N
predicted # of seedlings surviving	12.65155	13.92139	40
estimated surviving seedlings/acre/decade	12.62747	15.06951	40

Model Summary^b

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Durbin-Watson
1	.922 ^a	.850	.846	5.47068	1.859

- a. Predictors: (Constant), estimated surviving seedlings/acre/decade
- b. Dependent Variable: predicted # of seedlings surviving

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	6421.121	1	6421.121	214.550	.000 ^a
	Residual	1137.278	38	29.928		
	Total	7558.399	39			

- a. Predictors: (Constant), estimated surviving seedlings/acre/decade
- b. Dependent Variable: predicted # of seedlings surviving

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.900	1.134		1.674	.102
	estimated surviving seedlings/acre/decade	.851	.058	.922	14.648	.000

Coefficients^a

Model		95% Confidence Interval for B	
		Lower Bound	Upper Bound
1	(Constant)	-.397	4.196
	estimated surviving seedlings/acre/decade	.734	.969

a. Dependent Variable: predicted # of seedlings surviving

Residuals Statistics^a

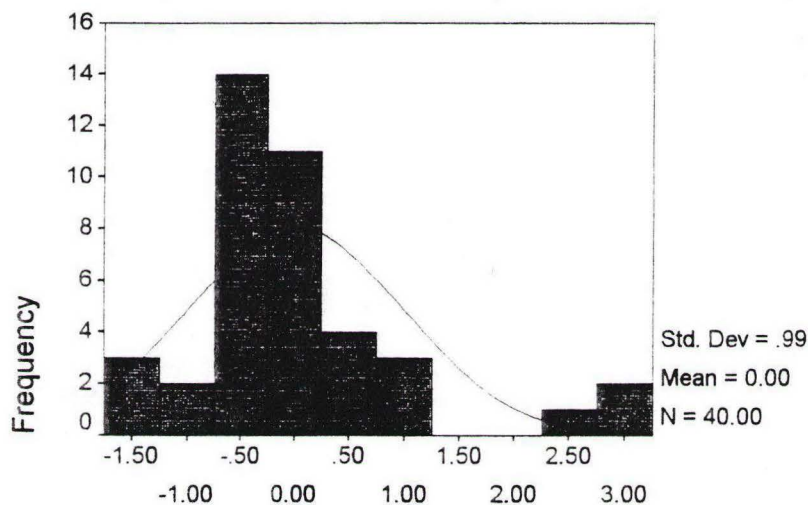
	Minimum	Maximum	Mean	Std. Deviation	N
Predicted Value	2.48599	64.06943	12.65155	12.83137	40
Residual	-8.25491	15.54948	-3.42E-15	5.40009	40
Std. Predicted Value	-.792	4.007	.000	1.000	40
Std. Residual	-1.509	2.842	.000	.987	40

a. Dependent Variable: predicted # of seedlings surviving

Charts

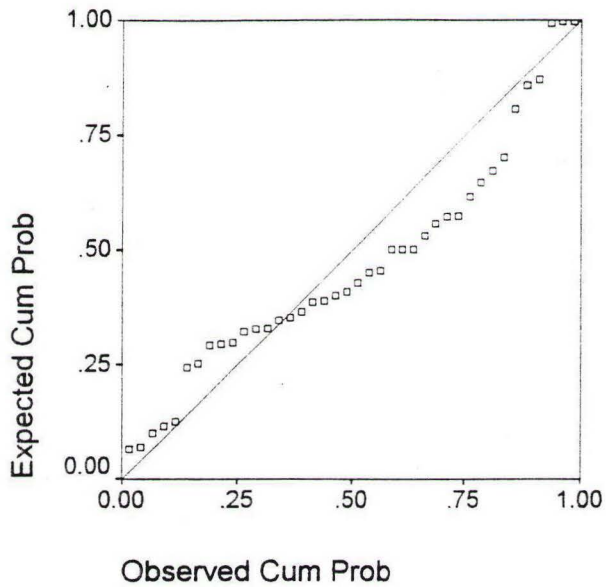
Histogram

Dependent Variable: predicted # of seedling

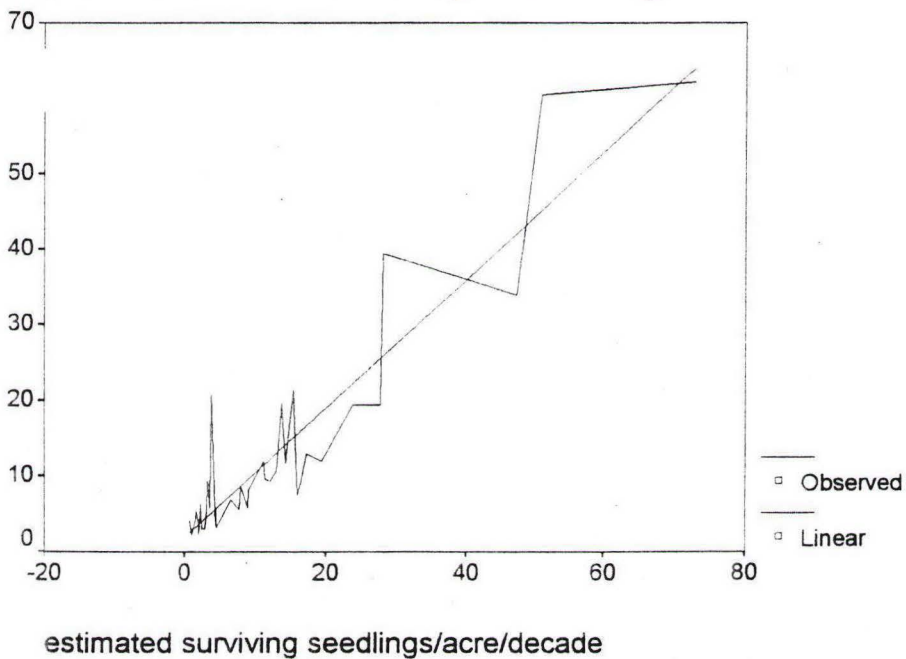


Normal P-P Plot of Regression Sta

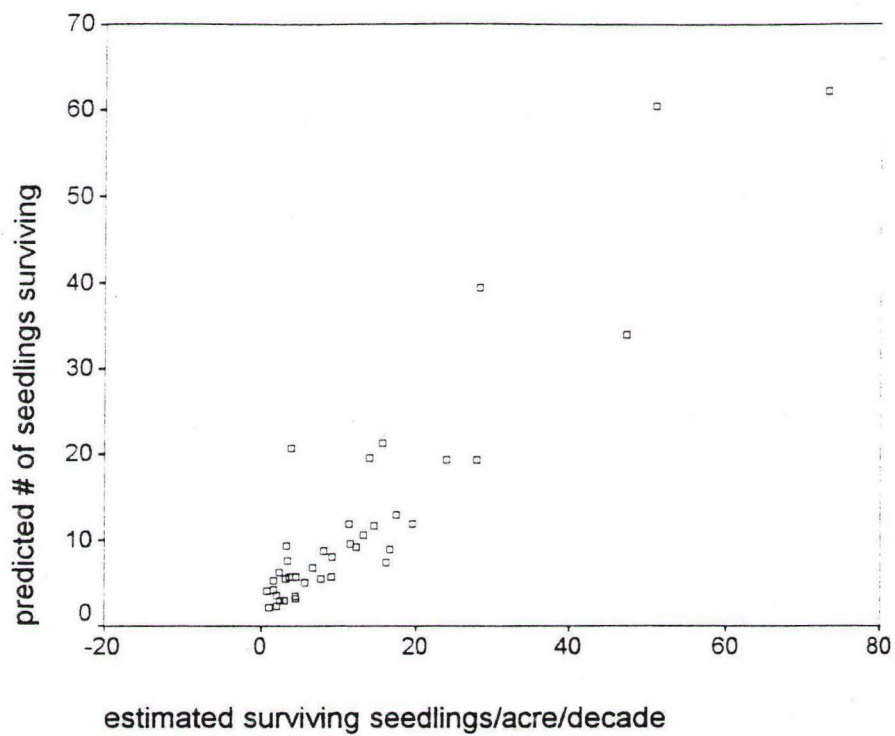
Dependent Variable: predicted # of



predicted # of seedlings surviving



Graph



6. Seedling Growth Rates and Effects of Browsing by Ungulates:

Susan Oberling, RM Station Archivist, located 72 photographs taken from 1928-1935 of a Forest Service study of post-cut ponderosa pine natural regeneration on the Coconino National Forest. The photographs show approximate annual height growth of 10-30cm on seedlings fenced from cattle and sheep. See the **attached photograph**.

Mean annual height growth of the seedlings mapped for this study is 3.50cm for seedlings lying on limestone soils and 3.05cm for seedlings on basalt soils. Mean annual height growth of the tallest quartile of seedlings is 4.35cm for seedlings on limestone soils and 3.59cm for seedlings on basalt soils.

Comparable mean height growth is greater for seedlings not under canopy than for seedlings under canopy or at the edge of the canopy. Canopy interception and greater needle litter depth under canopy will reduce total soil moisture. See the **attached table "Annual Seedling Height Growth"** and chart **"Mean annual height of seedlings"**.

Mean height growth appears to have no correlation with stand basal area. See the **attached chart titled "Relationship Between Seedling ... Basal Area"**. Mean annual height growth of seedlings in this study does not increase greatly as seedlings become older. Average annual height growth is 2.98cm for 3 year-old seedlings and 4.36cm for 12 year-old seedlings. The number of seedlings across all study plots declines considerably between ages 10 and 11 (174-61), and this decline does not appear to be associated with temperature or precipitation. The increase in seedling mortality at age 10 may be a reflection of cumulative stress caused by periods of drought, cohort competition for growing space (in some stands), browsing by cattle and elk, soil compaction, and loss of soil nutrients.

Fort Valley Experimental Forest records indicate that annual precipitation from 1928-1935 was well above average for the 20th century. We may assume this factor is partly responsible for the greater seedling height growth rates during this time. Precipitation can account for as much as 90% of variation in growth of trees (Kozlowski and Pallardy 1997). Even with one severe 18-month drought, the mean annual precipitation from 1988-1999 of 54.81cm approximates the mean annual precipitation from 1950-1999 of 56.01cm (NOAA 1999)

Other factors responsible for the decline over time in seedling height growth may be:

- * Less available growing space due to higher tree densities (not applicable to SH)
- * Higher soil bulk densities
- * Loss of incorporated soil organic matter
- * Repeated clipping of terminal growth leaders by cattle and elk

Photographs and field notes from the 1928-1935 Forest Service study of post cut natural pine regeneration on the Coconino National Forest illustrate the detrimental effects on regeneration and grass cover from grazing by cattle and sheep. Grazing intensity

monitored in the 1928-35 study appears to have been greater than it is today. See the **attached photograph**. However, today the ecosystem is responding not to one logging entry and a few decades of grazing, but to 80 additional years of continuous grazing and multiple logging entries.

During the summer and fall of 1999, Field Assistant Jessica Malan and I found that height growth leaders on 52% of the seedlings lying in the study plots had been clipped by ungulates. Clipping by rodents and damage from what appears to be thrips was minimal. On three occasions, cattle entered a study plot within 24 hours after we had mapped it. Each time this occurred, the number of clipped seedlings went from 0-10% to 60-100%. Due to the drought in the summer of 2000, browse damage for that year was not analyzed.

On May 16, 2001, five 1.3m square and 4ft high wire mesh cages were installed around seedlings to prevent browsing by elk and cattle. Each cage was located on one of five selected study stands, and each stand lies within one of five pastures on the Long Valley Ranger District. Seedlings in and around the cages were checked for browse on May 16, the day before cattle entered each pasture, the day after cattle left each pasture, and on October 31, 2001.

During the summer and fall of 2001, no rodent clipping or insect damage occurred on the seedlings enclosed by the five browse study cages. Damage to leaders of seedlings surrounding the cages from what appeared to be thrips was fairly extensive in May, but most of the seedlings grew new leaders during June. Among seedlings in a 10m square area around each of the five study cages, fewer than 5% exhibited at least one clipped leader before cattle entered the pastures.

Two of the cages were located in pastures where cattle grazed for 5-8 days. In the 10m square area around both cages, the number of browsed seedlings did not increase after cattle grazed the pastures; in fact, there was no evidence that the cattle had even entered the area. The remaining three cages were in pastures that were grazed by cattle for 3-4 weeks. After cattle left these pastures, the 10m square study area around each of the cages showed evidence of the presence of cattle. On average, 72% of the seedlings had at least one clipped leader. Inspection of the cages on October 31, 2001, found the average number of browsed seedlings around all five cages increased by 3% after cattle were removed.

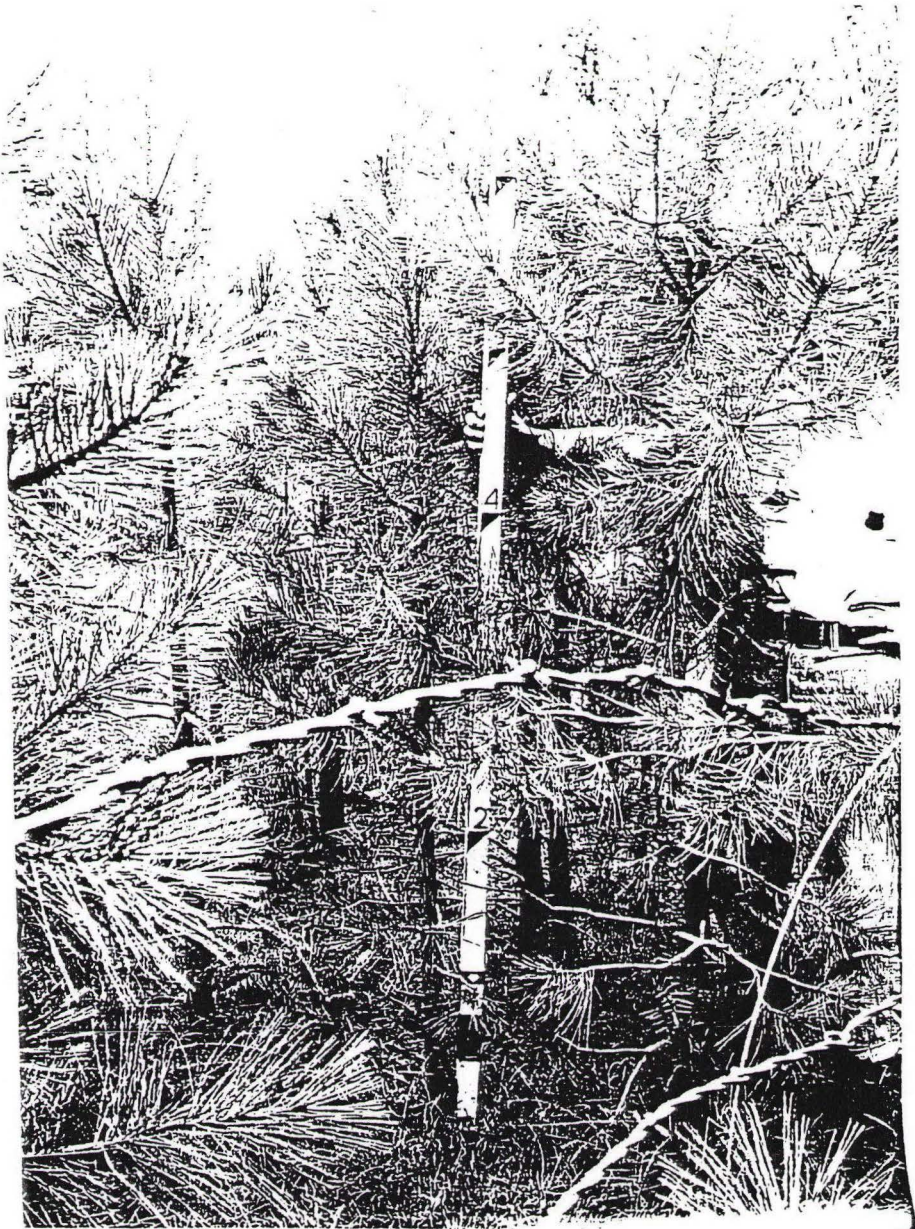
Cages were checked again on October 17, 2002. A spring and summer of extreme drought on the Coconino NF was followed with varying amounts of rain in August and early September. Cattle were not present during the growing season, but elk remained in the area. Eight percent of seedlings in the 10m square study areas around the cages had been browsed sometime during the 2002 growing season.

At the end of the 2002 growing season, current year height growth on seedlings within the 10m square study area around each of the cages was on average 154% of height growth for the previous year. Height growth of seedlings inside the cages was on average

175% of the previous year. Density of newly germinated seedlings inside the cages was on average 2.95 times greater than in the surrounding study areas. All new seedlings, both inside and outside the cages, were located in light litter. No seedlings greater than five years of age had died within the 10m square study areas.

An informal survey across the 47 study stands in mid-October, 2002, found that 94% of seedlings five years of age and older had survived the extreme drought. Seedling height growth appeared to have been delayed until after soil moisture was replenished by the late summer rains, as elongation of the terminal growth leaders was not entirely completed. Seedling response to the summer 2002 drought illustrates the adaptations to drought that *va. Scopulorum* exhibited in a study by Monson and Grant (1989).

In four of the five cages, the number of grass clumps and forb plants had approximately doubled since October, 2001. Each of the four cages contained species of grasses and forbs that had not been present the previous year. New species are wheatgrass, fescue, bluegrass, pussytoes, buckwheat, and vetch. The positive changes in vegetative productivity within the cages during 2002, a year of extreme drought, are hopefully reflecting the strength of the inherent resiliency remaining within this ecosystem.



**Annual Seedling Height Growth
In Centimeters**

	<u>n</u>	<u>$\bar{x}$</u>	<u>75th Percentile</u>	<u>Maximum Indiv.</u>
All stands, seedlings not under canopy	1093	3.51	4.33	25.00
All stands, seedlings under canopy	548	3.14	3.90	11.00
All stands, seedlings at canopy edge	368	3.28	3.80	11.40
Basalt stands, seedlings not under canopy	273	3.41	4.00	25.00
Basalt stands, seedlings under canopy	219	2.67	3.33	7.29
Basalt stands, seedlings at canopy edge	129	2.94	3.50	10.25
Limestone stands, seedlings not under canopy	820	3.54	4.58	12.92
Limestone stands, seedlings under canopy	329	3.46	4.27	11.00
Limestone stands, seedlings at canopy edge	239	3.46	4.00	11.40

Mean annual height of seedlings: under canopy - no canopy - edge of canopy

Report

HTPRYEAR

2=canopy 1=no canopy 10=edge	Mean	N	Std. Deviation
1	3.5085	1093	2.0788
2	3.1434	548	1.6240
10	3.2776	367	1.5906
Total	3.3666	2008	1.8861

Oneway

Test of Homogeneity of Variances

HTPRYEAR

Levene Statistic	df1	df2	Sig.
16.650	2	2005	.000

ANOVA

HTPRYEAR

	Sum of Squares	df	Mean Square	F	Sig.
Between Groups	52.204	2	26.102	7.384	.001
Within Groups	7087.517	2005	3.535		
Total	7139.721	2007			

Post Hoc Tests

Multiple Comparisons

Dependent Variable: HTPRYEAR
LSD

(I) 2=canopy 1=no canopy 10=edge	(J) 2=canopy 1=no canopy 10=edge	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1	2	.3651*	9.841E-02	.000	.1721	.5581
	10	.2309*	.1134	.042	8.425E-03	.4533
2	1	-.3651*	9.841E-02	.000	-.5581	-.1721
	10	-.1342	.1268	.290	-.3829	.1145
10	1	-.2309*	.1134	.042	-.4533	-8.43E-03
	2	.1342	.1268	.290	-.1145	.3829

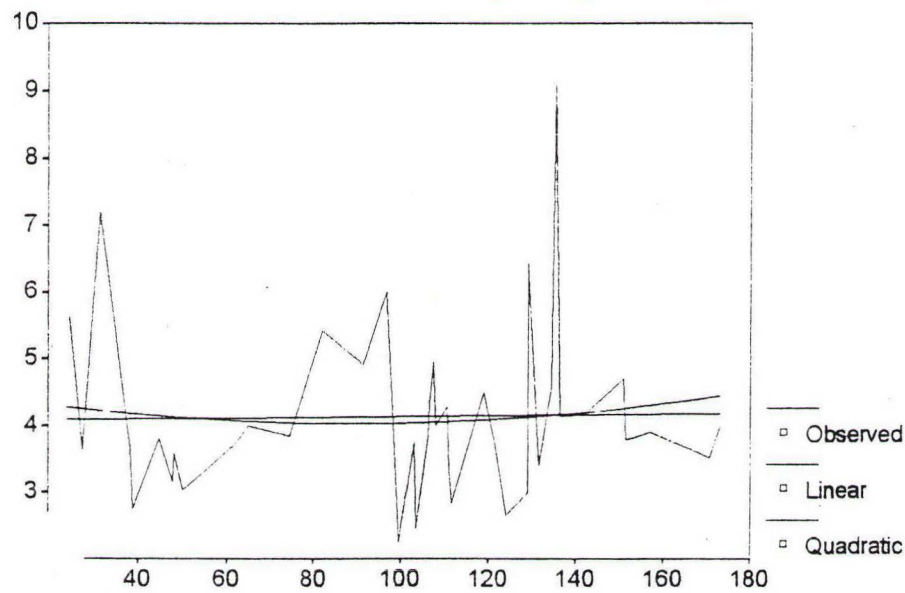
* The mean difference is significant at the .05 level.

Relationship Between Seedling Annual Height Growth and basal area

Independent: BAFRTREE

Dependent	Mth	Rsqr	d.f.	F	Sigf	b0	b1	b2
MNHTYR	LIN	.000	39	.02	.901	4.0764	.0006	
MNHTYR	QUA	.006	38	.12	.888	4.4999	-.0105	5.9E-05

mn 75percentile seedling ht growth/yr in cm

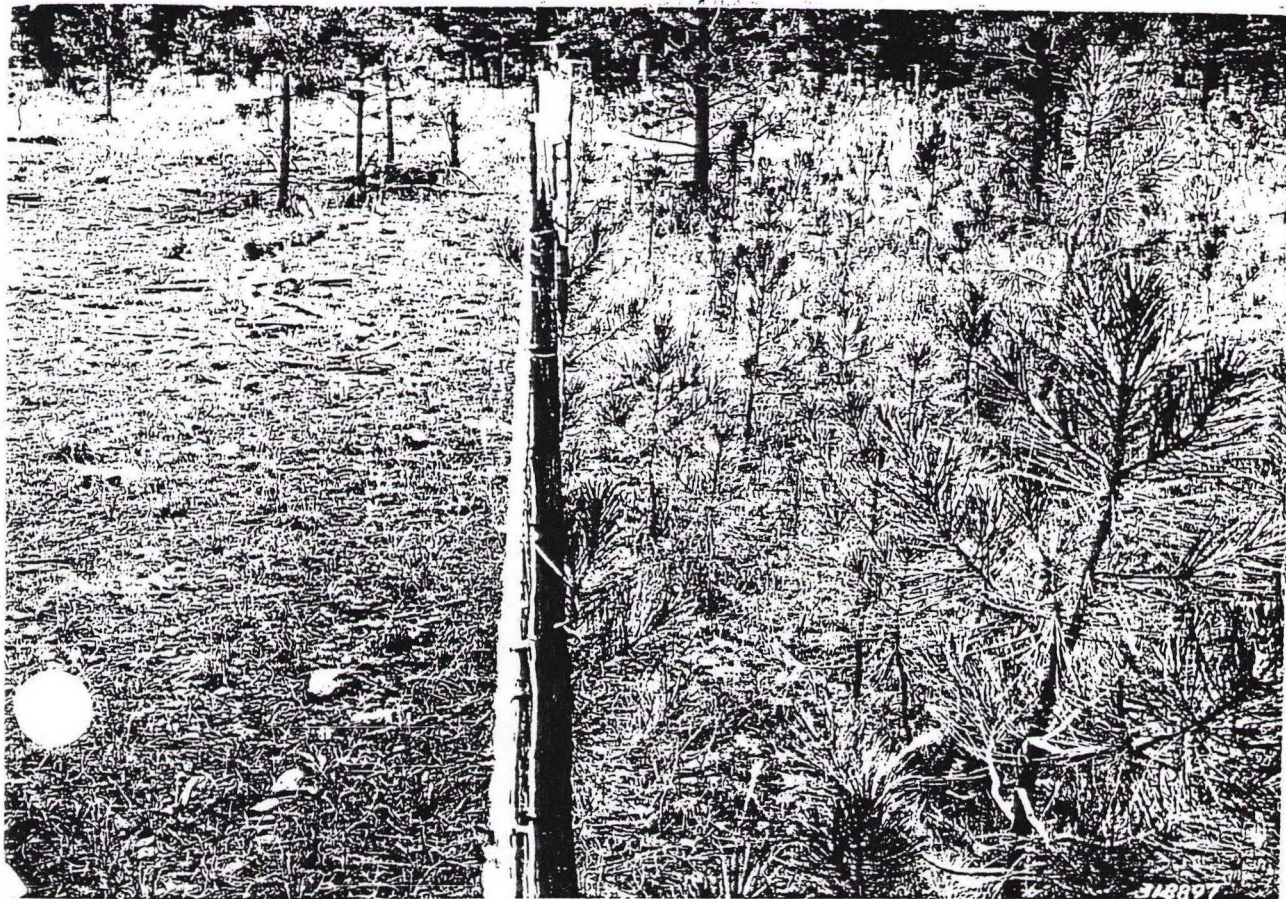


ba computed from tree dbhs >.38"

8/ 5. Rogers Lake Plot. Taken from the middle of the E. fence looking S. along the fence. Picture contrasting size and abundance of pine reproduction inside and outside the plot. Area inside plot on right half of picture. W. J. Cribbs.

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7. Seedlings are Growing In...

See the attached table "What Seedlings are Growing In".

Sheltered Microsites:

Seedlings appear to be selecting for sheltered microsites. The most preferred microsite is "by large dead & down logs", with "by rocks" and "by scattered slash" next in order of preference. Falling seeds are likely caught against logs, rocks and slash. Once there, the seeds are protected from predation by rodents, birds, and insects. Young seedlings are subsequently sheltered from browsing and from extreme heat, cold, and drought. Soils next to logs often have more incorporated organic matter and lower bulk densities, which may reduce frost heaving. One preferred microsite for successful seedling germination is "by scattered slash," despite an apparent negative correlation between high seedling density and high levels of slash on the ground.

Thin Litter Layer:

Seedlings appear to be selecting against deep needle litter and bare soil and for a thin litter layer. The preference for a thin litter layer is found among seedlings of all ages from 0-12 years, so it is not entirely the result of needle litter fall in the years following seedling germination. In contrast to bare soil, a thin litter layer likely provides some protection of the soil surface from erosion, temperature extremes, and evaporation. Litter may also protect seeds from predation by rodents, birds, and insects. Additionally, seedlings may be benefiting from the nitrogen that is leached from needle litter for 2-6 years after senescence (Klemmedson et al 1985). However, a deep litter layer intercepts a significant portion of precipitation and may keep the soil too cold for efficient litter decomposition and for seedling germination and establishment. During light rains and snowfalls, deep litter can capture all precipitation.

Needle litter is slowly decomposing, incorporating into the soil and reducing soil bulk density in the upper horizons. Across the stands in this study, litter in depths greater than 4cm rarely occurs, and litter depths exceeding 7cm are found only where it has blown into depressions in the ground or against large downed logs and tree trunks. The degree to which prescribed fire might reduce soil bulk density on the Coconino is unknown and needs to be investigated. Post burn bulk densities on the one study stand that underwent a prescribed fire are comparable to similar unburned study stands in the area.

Grasses:

Study stands average 7.0% of ground covered in grass basal stems, and no stand exceeds 21.3%. In this study, only a positive correlation was found between percent of grass basal stem and density or growth rate of seedlings; thus, we may tentatively assume that the present amount of grass cover is not great enough to significantly compete with seedlings. Results of this study cannot determine the minimum percent or type of grass

cover that would impede seedling establishment and growth. Pearson (1942) estimated that an unclipped grass cover of 50% or greater would be detrimental to seedlings.

Among the study stands on basalt soils, Pearson Correlations indicate that rates of pine regeneration are better where grass density is relatively high. Grass may be sheltering young seedlings in openings where tree canopy is not near to provide some relief from temperature extremes. The presence of grass in relative abundance may be indicative of soils with low bulk densities and relatively high levels of incorporated organic matter.

<u>All SH Stands</u>	<u>Pearson Corr.</u>	<u>Sign.(2-tailed)</u>
% ground in grasses - % seedlings not under can	.492	P=.087
<u>Basalt SH and DOG Stands</u>		
% ground in grasses - % seedlings not under can	.420	P=.105

With grass densities relatively low, needle litter in the study stands appears to be the primary agent preventing sheet erosion and reducing soil bulk density. In addition, litter likely is providing a source for carbon and nitrogen cycling, as well as microsite habitat for current and future seedlings. If needle litter is frequently consumed in prescribed fires, what will become its equivalent in the ecosystem? One goal of restoration management is to replace needle litter with grass. Grass may only functionally replace needle litter if impacts from current levels of grazing by elk and cattle are reduced to a level that allows establishment of the extensive and vigorous grass cover desired in the restoration model.

To maintain a suitable environment for seedling establishment, prescribe fire only if the mean needle litter depth in openings exceeds 3.0cm. Burning under conditions that should leave a thin unburned litter layer remaining on the soil surface. Burning shortly before the monsoons are to begin, when nights are warm and humidity is increasing, would allow smoke to disperse more quickly and would permit grasses to sprout within days after the burn. In addition, a new needle layer would be deposited on bare soil within 2-3 months.

What Seedlings Are Growing In

The column "Ratio A/B" is an indication of whether or not seedlings are selecting for or selecting against the ground cover type; ie, whether the ground cover type benefits (Ratio A/B >1.00) or deters (Ratio A/B <1.00) seedling germination and early survival.

<u>A. % seedlings growing by -</u>	<u>B. % ground covered in -</u>	<u>Ratio A/B -</u>
Dead & down <24.9cm diameter		
all stands = 9.02	6.37	1.42
all 585 stands = 16.30	6.73	2.42
Dead & down >25.0cm diameter		
all stands = 4.02	0.74	5.43
all 585 stands = 6.20	0.36	17.22
Rocks		
all stands = 10.19	5.09	2.00
Litter <2.9cm deep		
all stands = 42.53	51.42	0.83
all DOG stands = 44.86	43.01	1.04
all SH stands = 33.88	48.33	0.73
Litter >3.0cm deep		
all stands = 8.28	18.06	0.46
Bare soil		
all stands = 4.94	7.40	0.67
all DOG stands = 4.57	4.03	1.13
all SH stands = 6.24	13.19	0.47

8. Years Since Last Burned:

Across all study SH stands, a fairly strong bivartiate correlation seems to exist between the number of years since last control burned, and both number of seedlings and number of seedlings per seed tree; seedling response is strongest immediately following fire. This correlation does not appear on DOG and CT stands.

<u>All SH Stands</u>	<u>Pearson Corr.</u>	<u>Sig. (2-tailed)</u>
Years since burned & #seedlings/acre	-.412	P= .161
Years since burned & #seedlings/seed tree	-.416	P= .157

Mountain muhly is more prevalent in stands that have not been burned in many years; this relationship seems to exist on all TES soil types, but is strongest on TES 546 soils, where muhly is more prevalent. The only stand that has been fenced from cattle grazing for several (14) years has 8.50% of the ground covered in muhly basal stem. This is a 546 DOG stand, which was last logged in 1973, was precommercially thinned in the late 1970's, and has never been control burned. Among the 47 study stands, the next highest percent of ground covered in muhly basal stem is 6.10, and the average for all study stands is 1.79%.

<u>546 SH & DOG Stands</u>	<u>Pearson Corr.</u>	<u>Sig.(2-tailed)</u>
Years since burned & % ground in muhly basal	.716	P=.030

Burning the summer following a wet year, ie. when fertilization occurs but prior to autumn seed fall, could aid in stimulating regeneration on open stands the following summer by reducing needle litter depth and grass competition and by increasing soil nitrogen. The effect of burning on mountain muhly needs to be investigated.

9. Seedlings and Climate

Seedlings and Elevation:

The relationship between number of seedlings/acre and elevation is weak, yet the study data suggests a tendency for the number of seedlings/acre to be greater on stands that lie within the middle of the elevational range of ponderosa pine on the Coconino NF. See the **attached two charts "Relationship Between...and Elevation"**.

Seedlings and Precipitation:

Records from the Flagstaff Weather Station are used in this study, as they appear to be the only long-term and consistent source of weather data for all of the Coconino Forest. Even with the drought years, the mean annual precipitation from 1988-1999 of 54.81cm was close to the mean annual precipitation from 1950-1999 of 56.01cm. No correlation between temperature and total number of seedlings of each age could be found in this study. The number of seedlings of each age from 3-9 years appears to be strongly correlated to the mean annual precipitation of two years prior to germination, ie. to the year of pollination. Two consecutive wet years may not be necessary to produce high seedling numbers. No time frame except calendar year appears to correlate with seedling numbers. See the **attached chart "Independent ANNPREDI"**.

Above average precipitation may be necessary for the successful development of abundant staminate and immature ovulate cones. Development of these reproductive tissues requires less total expended energy than subsequent fertilization and embryonic development in the ovulate cones (Kozłowski and Pallardy 1997); however, abundant pollination may trigger the trees to allocate resources to ovulate cone development. Trees display reduced rates of cambial growth during years of abundant ovulate cone development (Kolb; pers comm.). Abundant seed production likely leaves more viable seeds after predation of immature cones and seeds, and it could ensure that more seeds will randomly fall onto suitable microsites. Suitable microsites would be those that capture or retain more water during subsequent dry years, provide shelter from midday heat, hold daytime heat longer through cold nights, or contain soils that are not compacted.

The two-year lag between abundant pollination and seed germination allows time to plan and implement management actions that could promote successful seedling establishment on stands needing regeneration. Actions might include thinning dense even-aged stands to create small irregular openings. Prescribed burning should be implemented prior to seed fall, so seeds are not consumed by fire.

Seedlings and Temperature:

On seven selected stands, precipitation, minimum-maximum temperatures, and soil moisture were recorded at approximately ten-day intervals from July 1– October 25, 2000, and from May 1 – August 24, 2001.

The seven stands selected for this aspect of the study are:

1. TES 582 SH - 6900' elevation - near Bar-M Canyon - cut in 1969 - mean ba 29sq ft/acre - canopy cover 9% - 5 seedlings/acre
2. TES 582 DOG - 6970' elevation - 0.25 miles from Stand 1 - mean ba 138sq ft/acre - canopy cover 41% - 35 seedlings/acre
3. TES 585 SH - 7390' elevation - south of Mormon Lake - cut in 1980 and 1991 - mean ba 16sq ft/acre - canopy cover 8% - 0 seedlings on stand
4. TES 582 CT - 7420' elevation - 0.3 miles from Stand 3 - cut between 1980 and 1990 - mean ba 126sq ft/acre - canopy cover 51% - 47 seedlings/acre
5. TES 585 DOG - 7480' elevation - south of Mormon Lake - mean ba 177sq ft/acre - canopy cover 54% - 83 seedlings/acre
6. TES 582 SH - 7360' elevation - west of Wing Mountain - mean ba 44 sq ft/acre - canopy cover 14% - 18 seedlings/acre
7. TES 582 DOG - 7680' elevation - south of Kendrick Peak - mean ba 110sq ft/acre - canopy cover 34% - 18 seedlings/acre

Elevation was derived at each site with a GPS unit. At two sites (Sun and Shade) within each stand but not visible from a road, minimum/maximum temperatures were recorded at a height of 0.5m from the ground. Prior to on site installation, temperature readings on all thermometers were checked and found to be consistent with one another. One thermometer in Stand 1 was destroyed by a bullet in September, 2000. The replacement thermometer was positioned next to the other thermometer in Stand 1 for ten days to verify its accuracy. It was then placed in its proper position.

On Stands 1, 2, 3 and 5, each Sun site was located in the center of a 12x12m (approximate) opening, and each Shade site was midway under the north facing canopy of a 50-60cm dbh tree situated on the opening edge and with a 4M crown class. The exception is the very open Stand 3, where the Sun site was in a large opening, and the Shade site was under the north-facing crown of an isolated tree. On the CT stand (Stand 4), the Sun site was in the center of a 9x9m opening, and the Shade site was in the center of a 12x12m clump of poles. On Stands 6 and 7, each Sun site was in the center of a 20x20m (approximate) opening, while each Shade site was in the center of a 15x15m (approximate) clump of poles.

The greatest difference in temperature (degrees Fahrenheit) between Sun and Shade sites on the same stand are listed in the **attached table "Within Stand Temperature Differences"**. Difference varied by up to 4 degrees among readings of each site. This was likely due to varying cloud cover, wind, and humidity over time. With the exception

of Stand 3, within stand temperatures of Shade sites remained warmer at night and cooler during the day than temperatures of Sun sites.

When stands are grouped by nearly equal elevation and are in close proximity, DOG and CT stands had warmer night and cooler day temperatures than SH stands. See the **attached table "Between Stand Temperature Differences"**. This trend holds between Stands 6 (SH) and 7 (DOG) at night, even though Stand 7 is the exception, being 500' higher in elevation than Stand 6. Higher night temperatures in Stand 7 are likely due to a cold air sink originating on Kendrick Peak.

Among the seven stands, Stand 3 is the most open and had the coldest night temperatures throughout the year. A temperature of -22° was recorded in Stand 3 during the winter; the next coldest temperatures recorded were -13° in Stand 1 and -11° in Stand 6 (all SH stands). Stand 3 sits in a slight basin and likely is in a cold air sink. Stand 3 has not regenerated in 30 years, while Stand 1 has only 5 seedlings per acre after 30 years.

Temperature extremes appear to be moderated under tree canopy, and this moderating effect is greater where overall stand canopy is high, trees are clumped, and openings are small. With moderated temperatures, seedlings are likely at lower risk of wilting in summer, are less likely to be killed by cold or frost heaving in winter, and may benefit from an extended growing season.

Prior to thinning a stand to below 40% canopy, it would be advisable to monitor minimum and maximum temperatures over one year in both shade and in a large ($>30 \times 30\text{m}$) opening within or near the stand. If temperature extremes in the opening are near the tolerance of seedlings (-25°F), or if temperature differences between shade and opening are greater than $5-6^{\circ}$, then thinning to below 40% canopy could place the stand at risk of regeneration failure. Be particularly cautious of stands that are situated where cold air drainage may be a problem.

Seedlings and Soil Moisture:

Percent total soil moisture was measured in the top 15cm of soil at each Sun and Shade site on four of the seven stands where temperature was monitored. The four study stands were Stands 1,2,3, and 5 described above. A rain/snow gauge was installed on the same 5' post holding the thermometer in the center of each Sun site. Soil moisture probes were installed in the ground 0.5cm from the posts, and these probes remained in place for the duration of the monitoring. Soil moisture, along with minimum/maximum temperature and precipitation, was recorded at approximately ten-day intervals.

Monitoring in this study was minimal; a far more extensive investigation of soil moisture would be needed to obtain a good picture of differences in relative soil moisture among within-stand microsites and among stands. Nevertheless, the data does indicate a few trends worth mentioning. Note that for basalt soils on the Coconino NF, soil moisture at saturation is 47.7% and at field capacity is 35.4%.

From July 10 - July 20, 2000, no rain fell at the four study stands. This period of time was toward the end of a severe drought. On July 20, percent total soil moisture was:

- * Stand 1 [SH-elev. 6900'-grass 7.6%-BD1.80g/cc] Sun = 12.6% Shade = 11.7%
- * Stand 2 [DOG-elev. 6970'-grass 4.1%-BD1.36g/cc] Sun = 12.8% Shade = 11.8%
- * Stand 3 [SH-elev. 7390'-grass 21.3%-BD1.07g/cc] Sun = 13.5% Shade = 17.8%
- * Stand 5 [DOG-elev. 7480'-grass 6.0%-BD 0.99g/cc] Sun = 14.0% Shade = 13.3%

On July 20, soil moisture was below field capacity. Throughout the monitoring period, soil moisture was nearly always lower under tree canopy, due to interception from the crowns and greater needle litter depth. The differences between Sun and Shade sites listed above are typical for values taken when little or no recent precipitation was recorded.

Between August 15-25, 2000, from 0.65-2.52" of rain fell at the study stands:

- * Stand 1 [SH-elev. 6900'-grass 7.6%-BD1.80g/cc] Sun = 47.9% Shade = 33.9%
- * Stand 2 [DOG-elev. 6970'-grass 4.1%-BD-1.36g/cc] Sun = 34.9% Shade = 30.1%
- * Stand 3 [SH-elev. 7390'-grass 21.3%-BD-1.07g/cc] Sun = 19.4% Shade = 13.0%
- * Stand 5 [DOG-elev. 7480'-grass 6.0%-BD-0.99g/cc] Sun = 30.7% Shade = 32.6%

Stands 1 and 2 received nearly equal amounts of rain (they are 0.25 miles apart). Stand 1, with few trees and a fairly sparse grass cover, was now at the saturation point at its Sun site, while Stand 2 was at field capacity at its Sun site. Had the many trees in Stand 2 already absorbed the excess soil water, or was its less compacted soil able to reach field capacity more quickly after precipitation?

From October 15 - October 25, 2000, the four study stands received from 2.93-3.62" of precipitation. On October 25, soil moisture was:

- * Stand 1 [SH-elev. 6900'-grass 7.6%-BD-1.80g/cc] Sun = 59.9% Shade = 33.7%
- * Stand 2 [DOG-elev. 6970'-grass 4.1%-BD-1.36g/cc] Sun = 34.0% Shade = 30.9%
- * Stand 3 [SH-elev. 7390'-grass 21.3%-BD-1.07g/cc] Sun = 51.2% Shade = 24.8%
- * Stand 5 [DOG-elev. 7480'-grass 6.0%-BD-0.99g/cc] Sun = 34.1% Shade = 33.7%

By mid October, grasses would be dormant; thus the above soil moisture readings give a rough idea of the amount of soil moisture present when uptake by grasses is minimal on

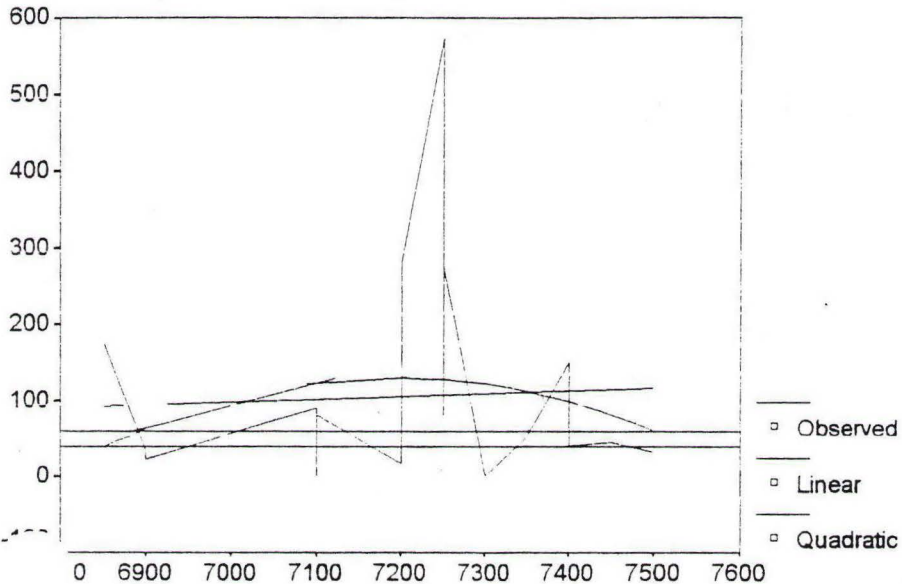
all four stands. The top 15cm of soils in both SH Sun sites are saturated, while the Sun sites in the DOG stands are near field capacity, as they were on August 25. The high bulk density of Stand 1 may explain the poor drainage of its soil. Stand 3 has a low bulk density at the 0-15cm soil depth. The poor drainage here likely is due to the location of the stand, which occupies a slight depression; soil compaction at depths below 15cm (presently unknown) may also be a factor. Based on remaining tree ages, Stand 3 appears to be an old meadow in which trees were able to establish during an extended drought prior to 1800.

Once established, ponderosa pine has the ability to develop deep root systems regardless of the moisture regime, but soil moisture near field capacity is ideal for the development of most tree species. Southwestern ponderosa pine germination and early survival has been shown to be dependent on moist but not saturated soils.

Relationship Between # Seedlings and Elevation - ES 546 and 650 Stands

De _i	ant Mth	Rs _q	d.f.	F	Sig _f	b0	b1	b2
NUMSEPC	LIN	.002	17	.04	.842	-162.05	.0372	
NUMSEPC	QUA	.042	16	.35	.709	-38934	10.8564	-.0008

#seedlings/acre age 3-12, post cut, adjusted for

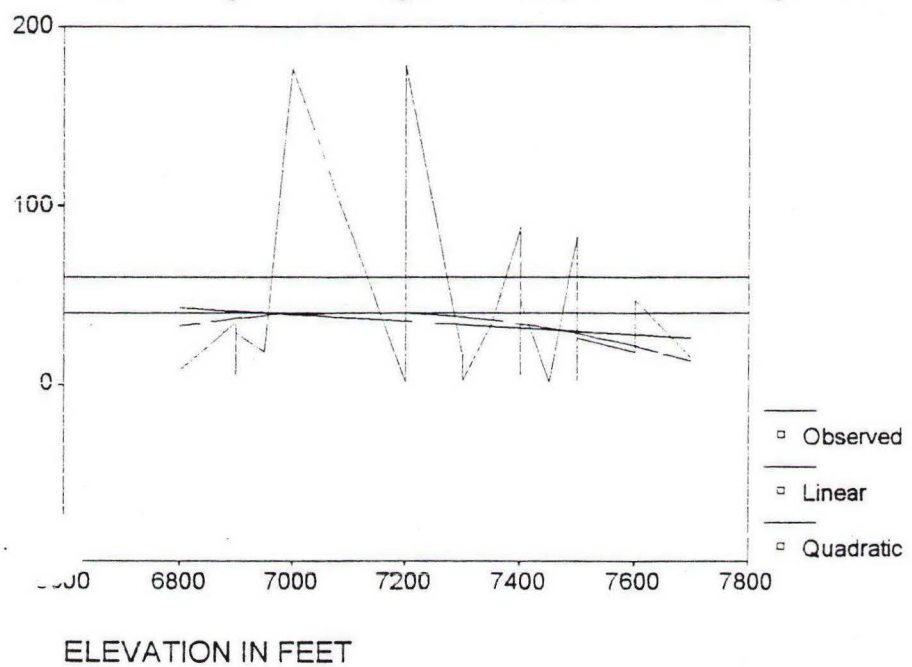


ELEVATION IN FEET

Relationship Between # Seedlings and Elevation - TES 582 and 585 Stands

Dependent	Mth	Rsqr	d.f.	F	Sigf	b0	b1	b2
NUMSEPC	LIN	.009	26	.25	.622	170.799	-.0188	
NUMSEPC	QUA	.020	25	.25	.779	-3978.3	1.1303	-8.E-05

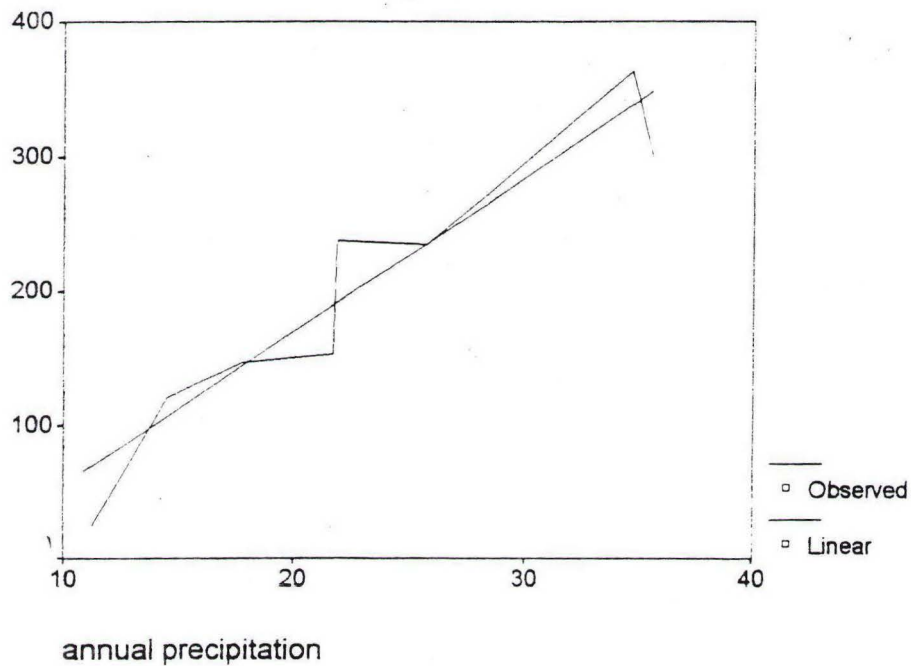
#seedlings/acre age 3-12, post cut, adjusted for



Ident: ANNPREDI

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1
NUMSEED3	LIN	.870	7	46.88	.000	-58.349	11.4330

number of seedlings, 3rd run



Within Stand Temperature Differences

(a) = July and August, 2000

(b) = September and October, 2000

(c) = Nov. 1, 2000 – May 1, 2001

Stand 1 SH – Min. night = Shade was (a) 3° (b) 1° (c) 9° warmer than Sun
Max. day = Shade was (a) 4° (b) 6° (c) 1° cooler than Sun

Stand 2 DOG – Min. night = Shade was (a) 5° (b) 3° (c) 10° warmer than Sun
Max. day = Shade was (a) 4° (b) 5° (c) 1° cooler than Sun

Stand 3 SH – Min. night = Shade was (a) 3° (b) 2° warmer and (c) 5° colder than Sun
Max. day = Shade was (a) 2° (b) 3° (c) 3° cooler than Sun

Stand 4 CT – Min. night = Shade was (a) 3° (b) 1° (c) 4° warmer than Sun
Max. day = Shade was (a) 2° (b) 2° (c) 1° cooler than Sun

Stand 5 DOG – Min. night = Shade was (a) 1° (b) 1° (c) 2° warmer than Sun
Max. day = Shade was (a) 4° (b) 4° (c) 1° cooler than Sun

Stand 6 SH – Min. night = Shade was (a) 3° (b) 2° (c) 2° warmer than Sun
Max. day = Shade was (a) 4° (b) 3° (c) 4° cooler than Sun

Stand 7 DOG – Min. night = Shade was (a) 9° (b) 2° (c) 3° warmer than Sun
Max. day = Shade was (a) 8° (b) 3° (c) 4° cooler than Sun

Between Stand Temperature Differences

(a) = July and August, 2000

(b) = September and October, 2000

(c) = Nov. 1, 2000 – May 1, 2001

Stand 1 SH & Stand 2 DOG --

Sun: Min. night = DOG was (a) 6° (b) 8° (c) 9° warmer than SH
Max. day = DOG was (a) 4° (b) 3° (c) 1° cooler than SH

Shade: Min. night = DOG was (a) 4° (b) 4° (c) 8° warmer than SH
Max. day = DOG was (a) 4° (b) 4° (c) 2° cooler than SH

Stand 3 SH, Stand 4 CT & Stand 5 DOG --

Sun: Min. night = DOG was (a) 10° (b) 11° (c) 13° warmer than SH
 CT was (a) 11° (b) 9° (c) 12° warmer than SH
 Max. day = DOG was (a) 4° (b) 1° (c) 0° cooler than SH
 CT was (a) 2° (b) 2° (c) 2° cooler than SH

Shade: Min. night = DOG was (a) 7^o (b) 13^o (c) 20^o warmer than SH
 CT was (a) 6^o (b) 2^o (c) 21^o warmer than SH
 Max. day = DOG was (a) 3^o (b) 5^o (c) 0^o cooler than SH
 CT was (a) 2^o (b) 3^o (c) 2^o cooler than SH

Stand 6 SH & Stand 7 DOG –

Sun: Min. night = DOG was (a) 3^o (b) 4^o (c) 4^o warmer than SH
 Max. day = DOG was (a) 1^o (b) 1^o (c) 0^o cooler than SH
 Shade: Min. night = DOG was (a) 2^o (b) 4^o (c) 5^o warmer than SH
 Max. day = DOG was (a) 1^o (b) 1^o (c) 0^o cooler than SH

10. The “Ideal” Stand for Sustained Regeneration:

If ground fire were prescribed once every 20 years rather than once every 10 years, then approximately 40 3-12 year old seedlings/acre/decade might suffice to replace dying mature trees:

$$\begin{aligned} & 40 \text{ seedlings} && \times 0.55 \text{ (\% seedlings not under canopy)} \\ & && \times 0.22 \text{ (survival rate in 1 prescribed fire)} \\ & && \times 0.327 \text{ (mortality from cohort competition)} \\ & = 1.58 \text{ seedlings/acre/decade} \end{aligned}$$

Sustainability is more likely assured when highly productive stands produce large numbers of seedlings, but such stands generally require periodic precommercial thinning.

Six of the 47 study stands have 40-60 3-12 year old seedlings/acre/decade; therefore, these stands have produced an “ideal” number of seedlings, given a decade of nearly normal precipitation and the current state of ecosystem health. No TES 585 stands have 40-60 seedlings, so the attached table includes the one 585 stand with more than 40 seedlings/acre. Note that higher basal areas on TES 650 (limestone pipo over mixed conifer) prevent the establishment of more than 60 seedlings/acre/decade. See the **attached table “Stands with 40-60 Seedlings/Acre.”** Based on the attached table, an estimated range of basal area in square feet/acre that produces the “ideal” number of seedlings for each soil type is:

- * TES 585 = 160+
- * TES 582 = 90-140
- * TES 546 = 60-150
- * TES 650 = 130+

Within the study stands on limestone soils, regeneration seems to establish well in full sun and on bare mineral soils. This may be partly due to slightly greater than average mean precipitation across much of the Coconino where limestone soils occur. However, some study stands on basalt soils also have average mean precipitation values that are comparable to those on limestone soils, but less regeneration. Soil moisture and nutrient characteristics likely account for much of the disparity in regeneration response.

For decades on the Coconino Forest, the standard prescription for regenerating a stand has been to shelterwood cut, machine pile slash, and machine scarify the ground. The notion was that the best regeneration response would occur on bare mineral soil and in full sun. This prescription has worked well on most limestone soils, usually resulting in a sea of seedlings within a few years after logging.

Unfortunately, ponderosa pine regeneration is not adequate on most basalt soil study stands where this prescription has been applied. On basalt soils, regeneration has been most consistent and most abundant in DOG stands where basal area is high and trees are multi-storied, openings are small, large dead and down wood is present, grass density is

moderate, and needle litter is extensive. This site description is quite contrary to the presettlement model for basalt soils around Flagstaff on the Coconino Forest.

Will basalt stands managed to simulate the presettlement model, ie. consisting of 20-30 primarily large mature trees and dense grass, have enough regeneration response to be self-perpetuating? After two summers of mapping presettlement trees and stumps, I believe the presettlement model for much of the area around Flagstaff is essentially correct. What I question is the assumption that the model is sustainable. With 20-30 trees per acre in 1850, basal area (thus canopy and seed source) may have been too low to provide adequate seed source and mitigate temperature extremes. Grasses may have been dense enough to out-compete seedlings, and fires may have been frequent enough to consume virtually all seedlings before they could outgrow the tall flames produced by dense grass fuels. The 1850 model we are trying to simulate around Flagstaff may well be that of an old forest ecotone converting to pinyon/juniper or grassland, the result of the extended dry period prior to 1800. In a semi-arid climate, few vegetative communities remain fixed in space over time.

Restoration prescriptions with low tree densities may be more suitable for limestone soils than for basalt soils. Until more is learned through monitoring about the effects of forest restoration on soils, microclimates, and grass/seedling competition, a conservative approach to managing stands on basalt soils would be advisable. To assure eventual regeneration on basalt soils, basal area would remain above 90sq ft/acre. Ideally, the ground would be covered with 20-30% grass basal stem and a thin layer of grass and needle litter. Large logs would be protected from ground fire, and a small amount of slash would be scattered in openings. Trees would be in loose clumps interspersed by small irregular openings, thus maximizing the beneficial effect of partial side shade on seedlings establishing in the openings. Thinning operations would leave and protect existing seedlings and saplings not under tree canopy.

Stands With 40-60 Seedlings/Acre

	TES 585 (1)	TES 582 (2)	TES 546 (1)	TES 650 (2)
# Seedlings	83	47, 47	52	41, 46
Elevation	7500	7400, 7600	7350	7400, 7450
% Canopy	54	51, 17	42	47, 44
QMD trees >9.9cm dbh	11.32	14.47, 18.88	18.29	12.97, 12.77
BA from trees	170.42	134.51, 64.76	99.58	156.96, 129.01
Years since cut	55	10, 10	25	NA, 25
Years since Burned	12	NA	7	NA, 100+
% ground in litter<2cm deep	24.50	52.2, 51.7	62.7	70.7, 49.3
% ground in dead & down <25cmd	10.20	7.9, 3.5	4.0	9.6, 6.2
% ground in grasses basal	6.0	4.5, 19.0	8.4	0.6, 0.9
% ground in bare soil	1.9	2.4, 5.9	4.6	3.3, 7.2
# seedlings per seed tree	3.9	0.61, 2.57	2.01	0.82, 3.03
adjusted bulk density gr/cc 1m from seedling	0.84	NA	0.79	1.28, 1.10
adjusted bulk density gr/cc in openings	0.99	1.58, 1.10	1.11	1.50, 1.30

11. Relationship of Basal Area and Canopy:

Percent of canopy cover is often used to help describe the structure of ponderosa pine vegetative communities in the Southwest, particularly when defining species-specific or use-specific wildlife habitat. Obtaining a reliable estimate of canopy cover for a given area requires extensive, and therefore expensive, point sampling with a vertical projector. In the name of efficiency and economy, foresters, biologists, and planners on the Coconino National Forest sometimes use the mean basal area of a given stand or area to estimate canopy cover. Fewer point samples are needed to obtain a reliable estimate of basal area, and the basal area of many stands is already on record. The rule of thumb for estimating canopy cover from basal area is: Basal area in square feet per acre is twice the percent of canopy cover. Therefore, if basal area is 100sq ft/acre, then canopy cover is approximately 50%.

On each study plot, both basal area and canopy cover were recorded, as described above in the Study Design. Based on the stand averages of study plot data, the relationship between basal area and canopy cover appears to be strong. As expected, this relationship is quadratic; however, the linear relationship is strong enough within the range of tree densities found on the study stands that, for the sake of practicality, it could be used to describe the ratio of basal area to canopy cover. See the **attached two charts** **“Relationship Between Basal Area and Canopy Cover”**.

The ratio of basal area to canopy cover was calculated for each study stand, and these have been grouped by soil type and stand management history in the **attached table “Stand Averages”- Column 3**. A summary of basal area, canopy, and the ratio of basal area to canopy calculated by plot is in the **attached table “Ratio of Basal Area to Canopy Cover”**.

Among the 47 study stands, the ratio of basal area in square feet/acre to percent canopy cover ranges from 2.12-4.57. The average ratio is 3.07/1.00. On average, if basal area is 100sq ft/acre, then canopy cover is approximately 33%.

Regarding the relationship between basal area and canopy cover, variation about the regression line is likely due to differences in spatial pattern, tree size, and tree genetics. If trees are spatially aggregated, the ratio of basal area to canopy cover should be greater than if the same trees were spatially dispersed. Crowns of clustered trees generally are intermingled or are short on the inside of the cluster; thus their crowns are not as wide as crowns of isolated trees. Smaller horizontal crown area per equivalent trunk diameter size equates to less canopy cover per equivalent amount of basal area.

Genetics likely also affects the ba/canopy relationship of ponderosa pine at the landscape scale, as the relative width of tree crowns appear to vary among the species' subpopulations in the Southwest.

In general, the ratio of an individual tree's basal area to its crown also appears to vary by tree age. The ratio of basal area to crown width appears to be less in poles and small sawtimber than it is in mature trees.

Theoretically, a multiple regression model of qmd and the ratio of Ripley's $K(t)$ function to $\pi(d)^2$ might be used to predict appropriate ba./canopy ratios for a variety of ponderosa pine stand structures. $K(t)$ is a statistical expression of spatial aggregation wherein values above 1.0 indicate spatial aggregation of points (in this case, of trees), while values below 1.0 indicate the points are more spatially dispersed than if they were randomly located.

For each of 41 randomly chosen study plots, the Duncan $K(t)$ program was used to derive a single value $[mnK(t)/\pi(d)^2]$ that expresses the degree of spatial aggregation among all trees greater than 10cm dbh on the plot. See the **attached titled "Ripley's $K(t)$ "**. This value plus the qmd of all live trees greater than 10cm dbh became the predictor variables to model the ba/canopy ratio for the plot. See the **attached 3 charts titled "Ba/canopy from qmd and $K(t)$; Relationship Between ba/canopy..."**. Both $[mnK(t)/\pi(d)^2]$ and qmd failed to estimate ba/canopy. The quadratic curves of the relationship between (1) ba/canopy and qmd, and (2) ba/canopy and $[mnK(t)/\pi(d)^2]$ merely hint at the relationships described above.

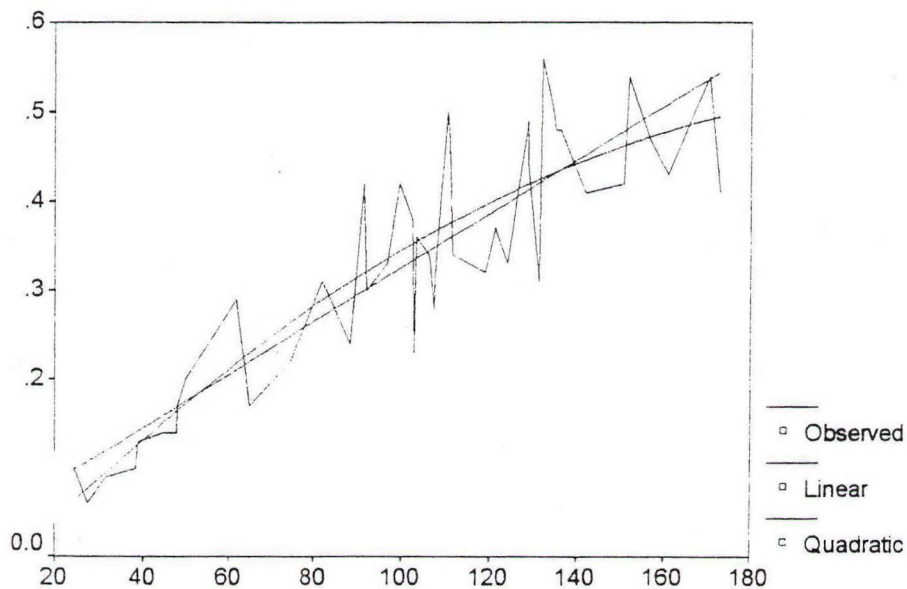
The weakness of the relationship is likely due to (1) the multi-aged structure of most of the study SH and DOG stands, (2) genetic differences in tree crown width, and (3) the tendency for thinning to homogenize the spatial structure of the remaining trees. The analysis of this relationship was done as an exercise in theory, as it has no practical application. It is far easier to measure canopy cover in the field with a vertical projector than it is to map all trees and process their x,y coordinates into a $K(t)/\pi(d)^2$ value!

Relationship Between Basal Area and Canopy Cover - BA from Tree DBH's

Indr dent: Mean Basal Area in square feet per acre

Dependent	Mth	Rsq	d.f.	F	Sigf	b0	b1	b2
CANOPY	LIN	.795	45	174.09	.000	.0252	.0030	
CANOPY	QUA	.814	44	96.50	.000	-.0557	.0051	-1.E-05

MEAN CANOPY FOR STAND



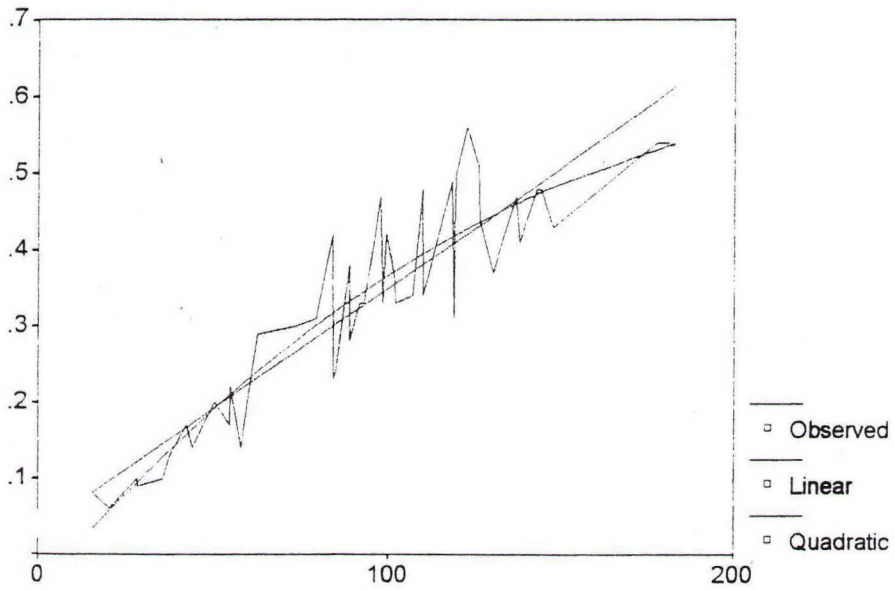
ba computed from tree dbhs > .38"

Relationship Between Basal Area and Canopy Cover - BA from 10x Angle Gauge

Independent: Mean Basal Area in square feet per acre

Dependent	Mth	Rsqr	d.f.	F	Sigf	b0	b1	b2
CANOPY	LIN	.815	45	198.80	.000	.0318	.0032	
CANOPY	QUA	.839	44	114.76	.000	-.0457	.0052	-1.E-05

MEAN CANOPY FOR STAND



ba (SQ FT/ACRE) computed from 10-factor angle gauge

Ratio of Basal Area to Canopy Cover

Select stands on Coconino National Forest

47 stands; 141 30m square plots; 30 points/plot; points located in a grid pattern across plot.

All plots (number of points = 4230):

Mean ba (sq ft, 10x angle gauge) = 93.54

Mean ba (sq ft, from tree dbh's) = 100.97

Mean percent canopy (overhead projection) = 32.89

Developing old growth plots (number of points = 1260):

Mean ba (10x) = 124.12

Mean ba (from trees) = 131.55

% canopy = 43.57

Shelterwood cut plots (number of points = 1530):

Mean ba (10x) = 54.73

Mean ba (from trees) = 62.23

% canopy = 20.59

Commercially thinned plots (number of points = 1440):

Mean ba (10x) = 108.01

Mean ba (from trees) = 115.38

% canopy = 36.63

All plots basal area/canopy (from trees) = 3.07/1.00

40% canopy = 123ba

DOG plots basal area/canopy (from trees) = 3.02/1.00

40% canopy = 121ba

SH plots basal area/canopy (from trees) = 3.02/1.00

40% canopy = 121ba

CT plots basal area/canopy (from trees) = 3.15/1.00

40% canopy = 126ba

Ripley's $K(t)$

Ripley's $K(t)$ is the average number of observations found within a circle of t radius, centered on an observation, and divided by the mean intensity of the process (the number of observations divided by the study area). Monte Carlo simulations of x, y point coordinates are run to generate a frequency distribution for a random pattern of point coordinates. The value of $K(t)$ for the given radius distance t is then compared to the value expected from a random pattern of point coordinates, which is πt^2 .

To derive a single value of spatial aggregation for each plot, a ratio was derived for each successive one-meter distance along a radius distance of 3-15 meters. The numerator of each ratio is the $K(t)$ calculated for the distance from plot tree locations, and the denominator is the value of $\pi(d)^2$ for the distance, which expresses a completely random spatial pattern for that radius distance. Ratios less than 1.00 indicate a spatial dispersion of trees, while ratios greater than 1.00 indicate spatial aggregation of trees. Ratios for the successive radius distances were then averaged to derive a mean ratio for all $K(t)$ distances for the plot. This ratio is expressed as " $\text{mn } K(t)/\pi(d)^2$ ".

Ba/canopy from qmd and K(t)

Variables Entered/Removed^b

Model	Variables Entered	Variables Removed	Method
1	mean K(t)/pi t sq , 3-15m diameter circle, plot QMD all trees >10cmd ^a		Enter

a. All requested variables entered.

b. Dependent Variable: ba/canopy ratio, all trees >10cmd

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.337 ^a	.113	.068	1.082751

a. Predictors: (Constant), mean K(t)/pi t sq , 3-15m diameter circle, plot QMD all trees >10cmd

ANOVA^b

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	5.846	2	2.923	2.493	.096 ^a
	Residual	45.722	39	1.172		
	Total	51.568	41			

a. Predictors: (Constant), mean K(t)/pi t sq , 3-15m diameter circle, plot QMD all trees >10cmd

b. Dependent Variable: ba/canopy ratio, all trees >10cmd

Coefficients^a

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	1.706	1.265		1.349	.185
	plot QMD all trees >10cmd	.140	.064	.335	2.174	.036
	mean K(t)/pi t sq , 3-15m diameter circle	-3.914E-02	.716	-.008	-.055	.957

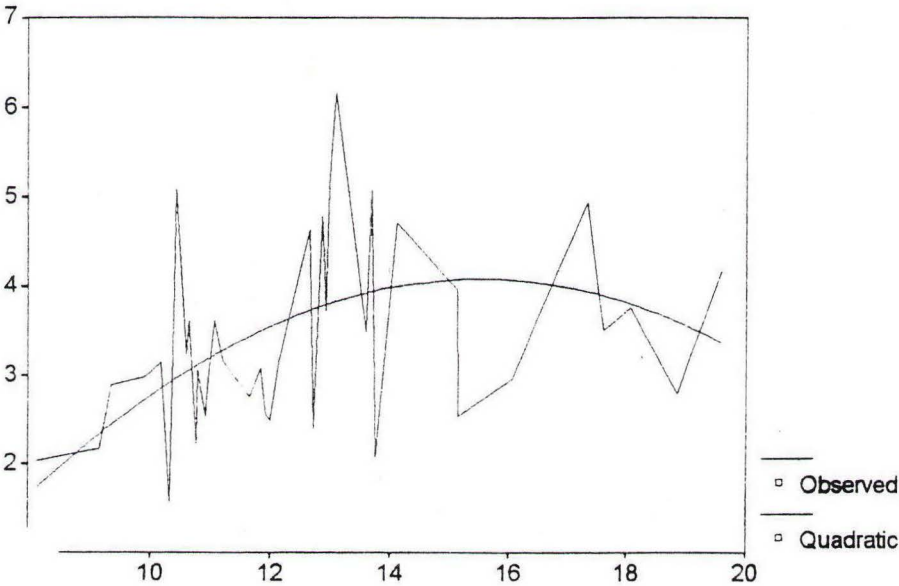
a. Dependent Variable: ba/canopy ratio, all trees >10cmd

Relationship Between ba/canopy and qmd - live trees >10cm dbh

Independent: QMD10CM

Dependent	Mth	Rsqr	d.f.	F	Sigf	b0	b1	b2
BACNRT10	QUA	.221	39	5.54	.008	-6.3177	1.3413	-.0432

ba/canopy ratio, all trees >10cmd



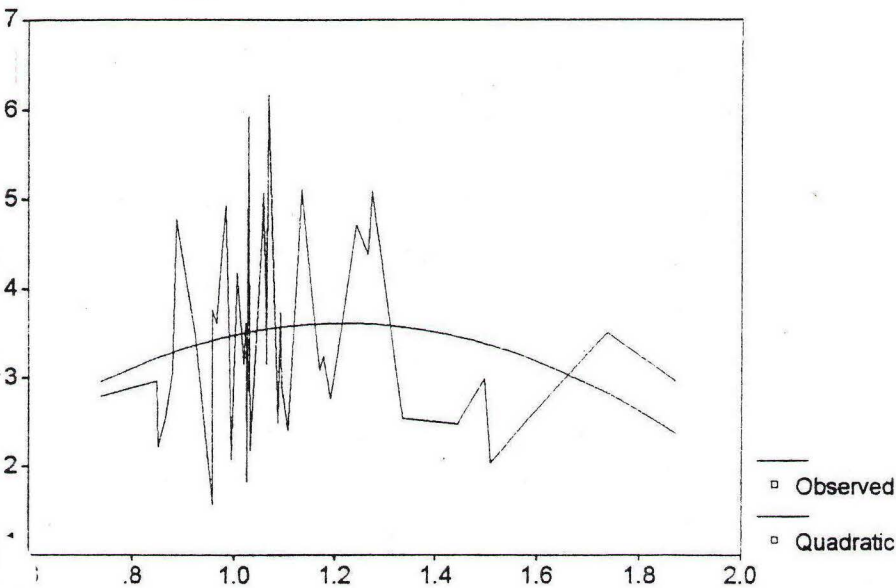
plot QMD all trees >10cmd

Relationship Between ba/canopy and K(t)/pi(d) - live trees >10cm dbh

Independent: KTPITSQ

Dependent	Mth	Rsqr	d.f.	F	Sigf	b0	b1	b2
BACNRT10	QUA	.046	39	.93	.402	-.6295	6.9913	-2.8792

ba/canopy ratio, all trees >10cmd



mean K(t)/pi t sq , 3-15m diameter circle